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MARTIN MARIETTA

Fallout Facts for Nuclear—Battlefield Commanders

C. M. Haaland

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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ABSTRACT

The basic phenomenology of radioactive fallout from nuclear detonations is described nonmathematically for military commanders who may become engaged in nuclear battle. Subjects include a description of fallout debris, the process of formation and deposition, and hazards to personnel. Comparisons are made between initial nuclear radiation and radiation from fallout. A radiation rate and exposure forecasting method is presented for situations where the source of fallout and rate of decay are unknown. Additional research is recommended for 1) development of improved methods for estimating casualties resulting from combined exposure to initial nuclear radiation and fallout radiation; and 2) improving the estimate of the K-factor (how much of the radioactive material comes to the ground as early fallout).

1. INTRODUCTION

In a tactical nuclear war, air bursts or deeply–buried detonations of nuclear weapons will usually be the preferred mode rather than ground–surface bursts. No commander will want to deliberately poison an area that may be occupied by his own troops within a day or so. However, tactical situations may arise where fallout may be either a desirable consequence or unavoidable. For example, a fallout strip may be laid down as a barrier to ground troop movement, or fallout may result from the necessity, possibly due to the lack of availability of deep–penetration warheads, to use ground–surface bursts against deep–buried command posts or weapons storage bunkers, or, ground–surface bursts may occur accidentally due to error in setting the detonation altitude before launch or due to misfire.

Fallout may exist in rear areas due to any one of the above reasons or due to a strategic laydown of nuclear weapons. Exposure to radiation from such fallout must be considered while evacuating casualties to the rear and during the period of convalescence.

Because exposure to fallout radiation can be lethal and the effects are additive to those from exposure to initial radiation, it is essential that battlefield commanders understand the mechanism of production of fallout, the hazards of fallout radiation, and means for measurement, protection and decontamination. This manual provides a brief overview of these topics, with references to basic sources. Expanded discussion is given on topics which are controversial, such as the fraction of total fallout that comes down as early fallout, the rate of decay of fallout radiation, and means for forecasting radiation rates and exposures.

In the past few years there has been a gradual changeover in the units of radiation measurement and dose. The old literature in this field has used the R (roentgen) as a unit of exposure to ionization in air, the rad for absorbed dose, and the rem for equivalent dose. In the new system of SI (Systeme International) units, the roentgen is not recognized, and the units for absorbed dose and equivalent dose are the gray (Gy) and the sievert (Sv), respectively. In this discussion of fallout radiation, there is frequent dependence upon valid research performed before the changeover in units. There has been no attempt to change units in drawings taken from old references to conform with the modern usage. For those unfamiliar with the old units, the roentgen was defined as the amount of x or γ radiation that produces 1 esu (electrostatic unit) of charge per cc of dry air at STP [Standard Temperature and Pressure, usually taken as 273 K (zero degrees C) and 760 mm Hg pressure]. It may be defined currently in equivalent units as producing 2.58×10^{-4} coulombs/kg in air, or as depositing 0.87 rad (a rad corresponds to the absorption of 100 ergs per gram) in air at STP. A roentgen of γ radiation in the energy range 0.1–3 MeV also produces 0.96 rad in tissue (ICRU62). The quality factor for γs in tissue in this energy range is unity. Hence, exposure of tissue to a given numerical quantity of γ radiation in the energy range 0.1-3 MeV will produce very nearly equivalent effects, regardless of expression of the quantity in units of roentgens, rads, or cGys.

Three lengthier sources of information on fallout may be consulted, *The Effects of Nuclear Weapons* (ENW77), *Structure Shielding Against Fallout Gamma Rays from Nuclear Detonations* (Sp80), and *Fallout: Its characteristics and management* (Fer83). For protective measures and operational procedures for radiation protection in shelters, *Radiation Safety in Shelters* (FE83) is recommended. Because of frequent citation, *The Effects of Nuclear Weapons* will be simply referred to as ENW77.

2. WHAT IS FALLOUT?

2.1 GENERAL

Fallout is the radioactive debris that comes back to earth after a nuclear explosion at the surface of the earth, or at an altitude low enough for the fireball to engulf solid materials. The fallout may consist of spherical or irregularly shaped particles ranging downward in size from that of coarse sand, some consisting of fine ash or crystals, or, farther downwind, consisting of very fine particles too small to be seen by the unaided eye. The nature of the fallout, that is, whether ashes, beads or crystals, depends on the composition of the materials engulfed by the fireball. The size of the particles will decrease with distance downwind. Sand–like particles will come to earth within a few kilometers from the detonation, but very fine particles may not reach the earth's surface until they have gone all around the earth several times.

Fallout is characterized by intense highly penetrating γ radiation from fission fragments, constituting a potentially lethal hazard to personnel in the vicinity, although β radiation may also cause injury under certain circumstances. Large areas, consisting of hundreds to thousands of square kilometers, depending on yield, can be covered with fallout from a single surface detonation, such that radiation from the contaminated area is hazardous or lethal to an unprotected person passing through or dwelling in the area, for periods of days to weeks after the detonation.

2.2 TYPES

Fallout may be characterized as 1) EARLY (also called "prompt" or "local") fallout, that which comes back to the earth's surface within 24 h after detonation, and 2) LATE or "delayed" fallout, which includes all fallout reaching the ground later than 24 h after detonation. Fallout may also be categorized as 1) SIMPLE, resulting from one or more detonations all having the same time of detonation, or 2) COMPOSITE, resulting from two or more detonations having different times of detonation. Simple fallout will have only one time of origin, i.e., all the fallout will have the same age. Composite fallout will have particles of different time origins, and the fallout is multi–aged. Radiation from composite fallout will decay more slowly than from any of its components taken separately.

EARLY fallout includes "stem" fallout, which consists of the heaviest particles in the fallout and is located in the vicinity of the stem of the mushroom cloud. Particles in early fallout are usually larger than about 20 microns (0.02 mm) diameter and fall within less than about 150 km from the detonation.

INTERMEDIATE fallout may be either early or late. This term is applied to fine particles that are injected into the troposphere below the tropopause. The tropopause refers to the region of the earth's atmosphere in which the temperature change vs altitude becomes positive rather than negative, as illustrated for the normal atmosphere in Figure 1. The altitude of the tropopause varies between about 7–17 km altitude, depending on latitude, season and local conditions (Ir80).

The fine particles of intermediate fallout result mainly from surface bursts of low-yield weapons, and require about three weeks to several months following detonation to reach earth (Co69). Intermediate fallout may therefore occur during periods of time that overlap early and late fallout.

A significant factor concerning fallout clouds at tropospheric or lower altitudes is that all or a portion of the clouds may be swept or washed down to the earth's surface by rain or snow. Radiation from such fallout may be much more intense than from fallout deposited by unaided falling in the atmosphere. On the other hand, if the rains are torrential, much of the fallout may be swept from exposed surfaces into the bottoms of rivers or into ditches or gulleys, where radiation may be significantly shielded by the depth of the water or by the surroundings.

LATE fallout may result either from intermediate fallout or from fine particles that have been injected into the stratosphere by large yield surface bursts.

2.3 CHEMICAL COMPOSITION OF FALLOUT: FRACTIONATION

The composition of fallout is greatly dependent on the composition of the materials that come in contact with the fireball. Fallout from weapons mounted on iron towers at the Nevada Test Site contained mostly iron oxides and glassy particles derived from melting of the silicate minerals of the soil below the tower (Ad60; Fr65; He70). Figure 2 shows a typical fallout particle from a tower shot in Nevada. Fallout from tests in the Pacific was dominated by a white ash containing calcites derived from the large volume of coral taken up by the fireball (Ad60; Is56; Le85). Figure 3 shows a typical fallout particle from a ground-surface shot at Bikini. The irregular shape and lower density of the Bikini fallout particles will result in a slower descent than that of the spherical particles from the Nevada tests. An extensive survey on the physical and radiochemical properties of fallout particles has been summarized by Crocker, et al. (Cr66).

The chemical composition of materials in the fireball changes rapidly in the first few minutes after detonation because the fireball cools quickly due to thermal radiation, expansion, and mixing with the ambient air. The cooling process is accelerated because the fireball rises by buoyant forces, lifting it to higher altitudes where the atmospheric pressure is lower, thus permitting a faster rate of expansion. The ratios of numbers of isotopes and atoms in the initial fallout will vary greatly for some materials as a function of time after the detonation, due to different physical properties of the elements, and the presence of gaseous elements in the decay chain (Fr64; Fr65; He70; Mi60a).

As an example of the influence of physical properties, some metals have higher vaporization and melting temperatures than other elements, and will, therefore, condense and solidify at an earlier time than the less refractory materials, leading to earlier fallout from the cloud. Other materials may become removed from the fallout cloud by transmuting to a gas in the radioactive decay-chain process, as, for example, the transmutation to xenon in the tellurium-iodine-xenon-cesium decay chain. These processes, described in some detail by Hicks (Hi82), are called fractionation.

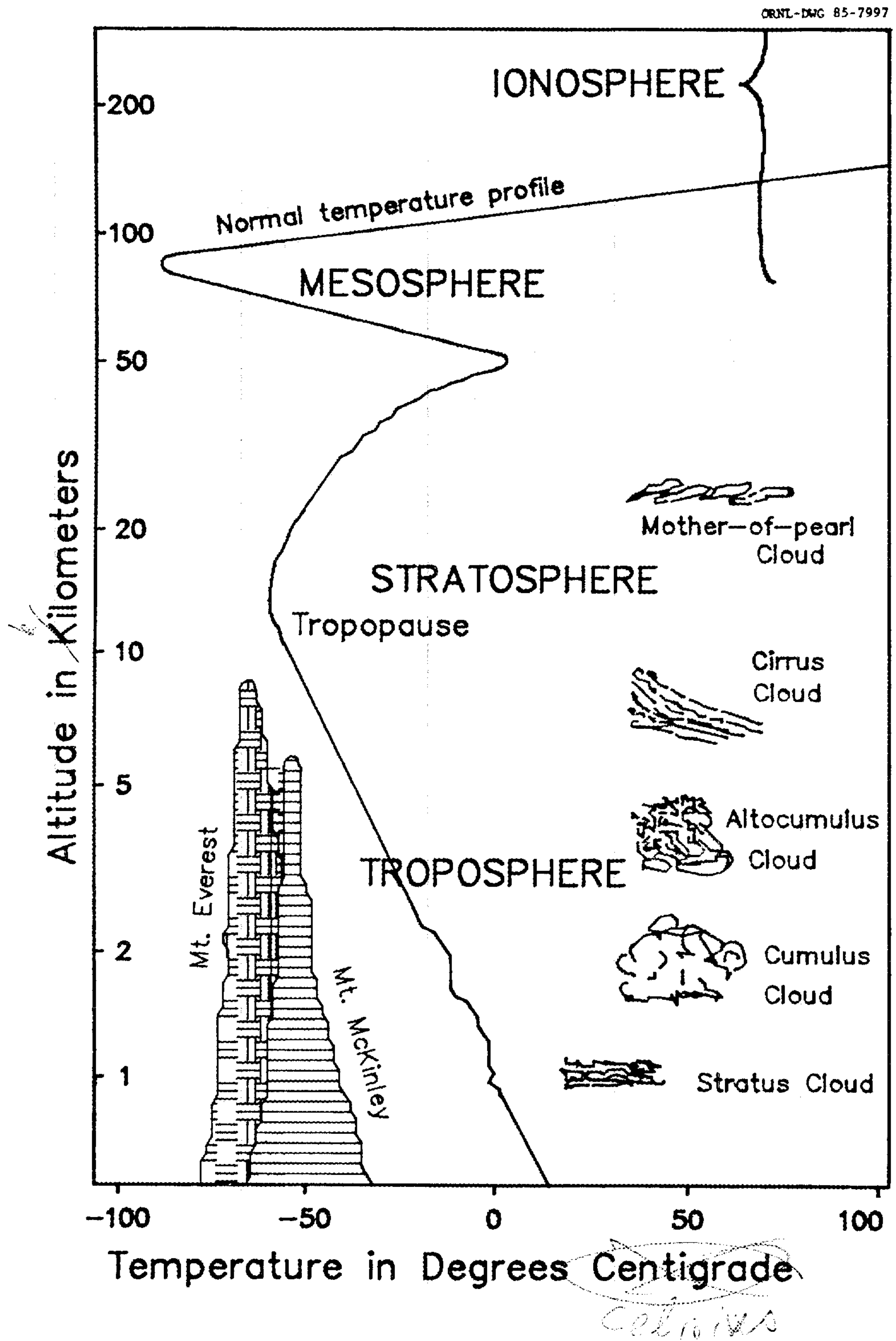

Figure 1. Temperature profile of the earth's atmosphere.

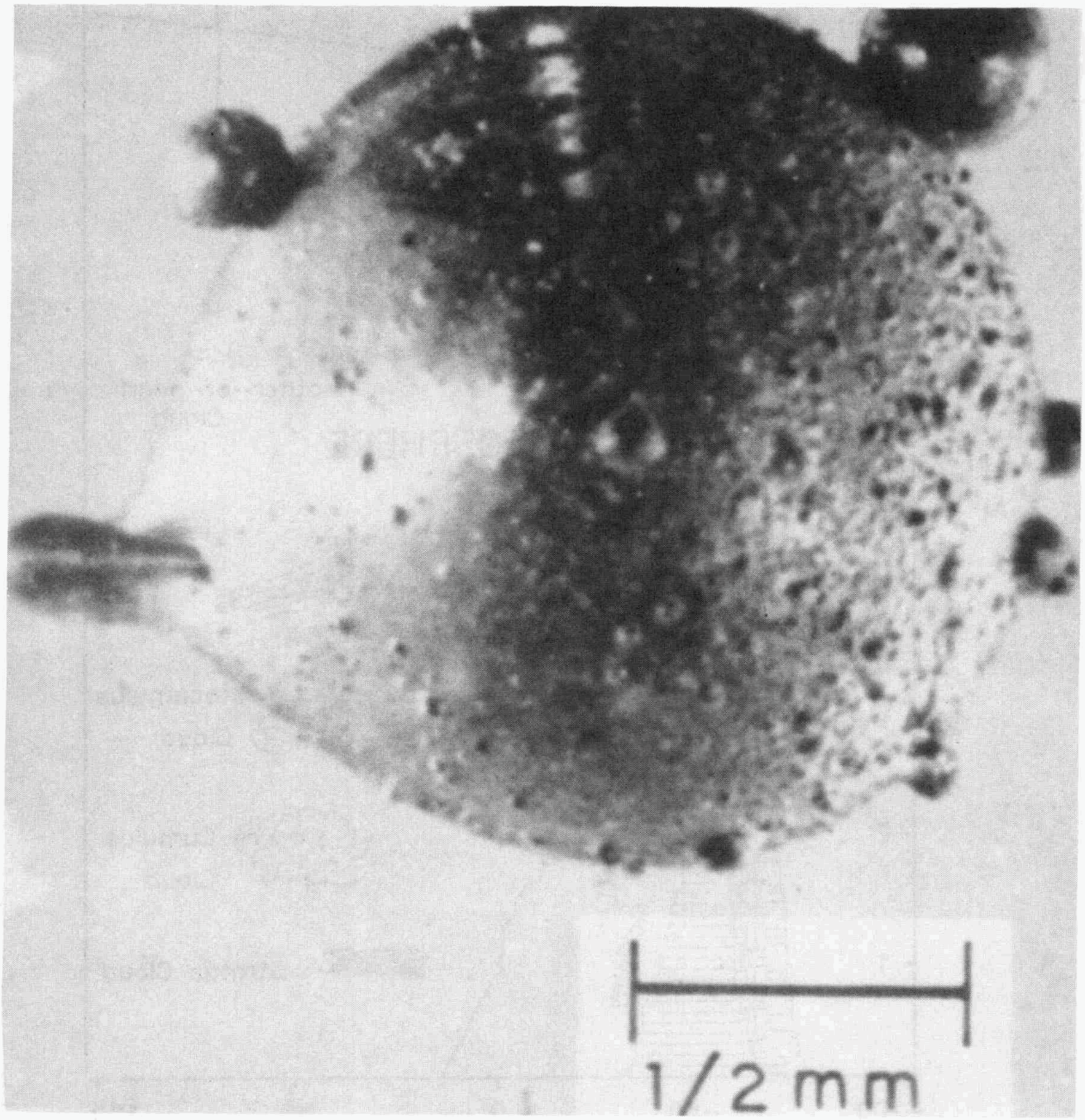

Figure 2. A radioactive fallout particle from a tower shot in Nevada. The particle has a dull metallic luster and shows numerous adhering small particles. From Crocker, et al., 1966.

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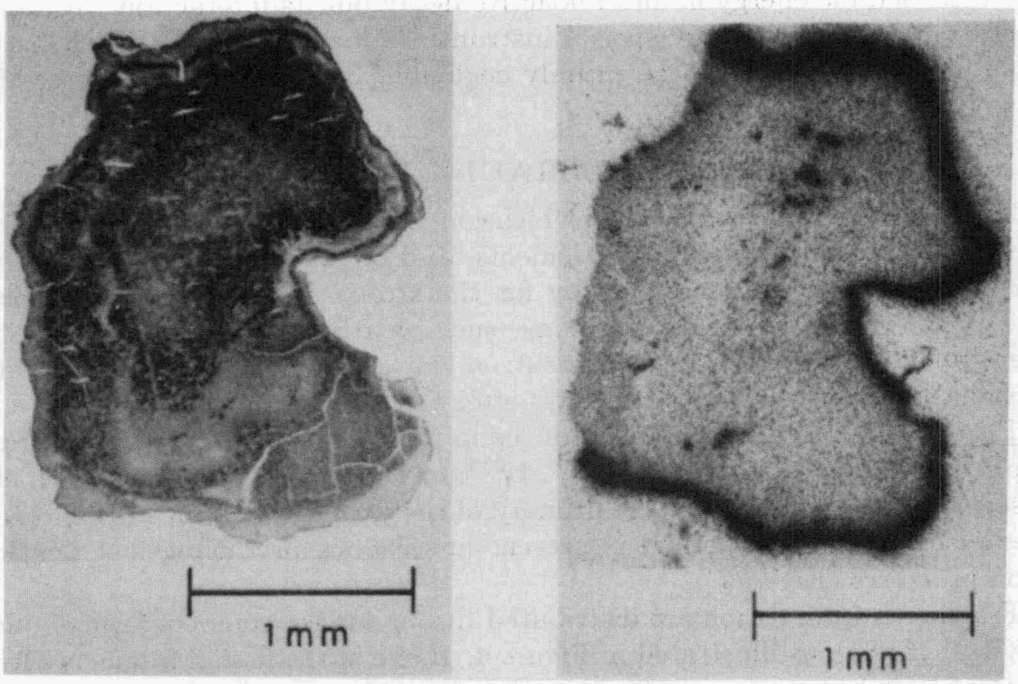

Figure 3. Photograph (left) and autoradiograph (right) of a thin section of an irregular particle from a ground-surface shot at Bikini. The radioactivity is concentrated on the surface of the particle. From Crocker, et al., 1966.

2.4 RADIATIONS FROM FALLOUT

Nuclear radiations from fallout are dominated by β and γ radiations, although α, neutron, and neutrino radiations are also present. Neutrino radiation carries away considerable energy in all radioactive decay but its interaction with matter is undetectable except by very special instrumentation. As a radiation hazard from fallout, neutrino radiations are entirely negligible and will not be discussed further here.

2.5 SOURCES OF RESIDUAL RADIATION

There are three types of sources which contribute to residual radiation: 1. fission fragments, 2. neutron–activated elements, and 3. unburned fissile materials. Of these three, fission fragments are by far the strongest contributors, although for some types of thermonuclear weapons, such as BRAVO, neutron activation can generate sufficient Np^{239}, through neutron capture by U^{238}, to strongly influence the radiation spectrum up to two days after the detonation (Le85).

Fission fragments are atoms produced in pairs from fission, which is the process of splitting a large atom such as U^{233}, U^{235}, or Pu^{239}, depending on which element is used in the construction of the primary of the weapon. Significant fission of U^{238} takes place when this element is present in weapons producing fast neutrons by fusion processes (ENW77).

Fragments from fission are distributed through mass numbers from about 70 to 165 (Ri81; En85), as illustrated in Figure 4. If one of the fission fragments from the fission of U^{235} has a mass of 160, the other fragment must have a mass of 72 or 73, depending on whether 2 or 3 neutrons are released during the fission. According to Figure 4, the probability of producing fragments with such a great difference in mass is less than one per 10,000 fissions.

Nearly all the initial fission fragments are radioactive, with half–lives ranging from fractions of a second to thousands of years. The predominant radiations from fission fragments are βs and γs. During the first few minutes after detonation some neutrons may be emitted in decay chains involving Kr 92–95 and Xe 141–142 because the neutrons are so loosely bound in the parent nuclei (We58). The number of these delayed neutrons becomes negligible within a few minutes after detonation, and, therefore, these radiations are not present in fallout on the ground. Alpha radiation from the heaviest fission fragments can occur, but this radiation is entirely negligible after the first few seconds after detonation. Alpha radiation from unburned fissile material may be significant, as discussed below.

Neutron activation occurs when a neutron produced by fission or fusion processes is captured by a nucleus, causing it to become unstable, with the subsequent emission of βs and γs. Induced radioactivity by a ground–burst fission weapon is much less intense than fission product radioactivity, as shown in Figure 5 (Ba60).

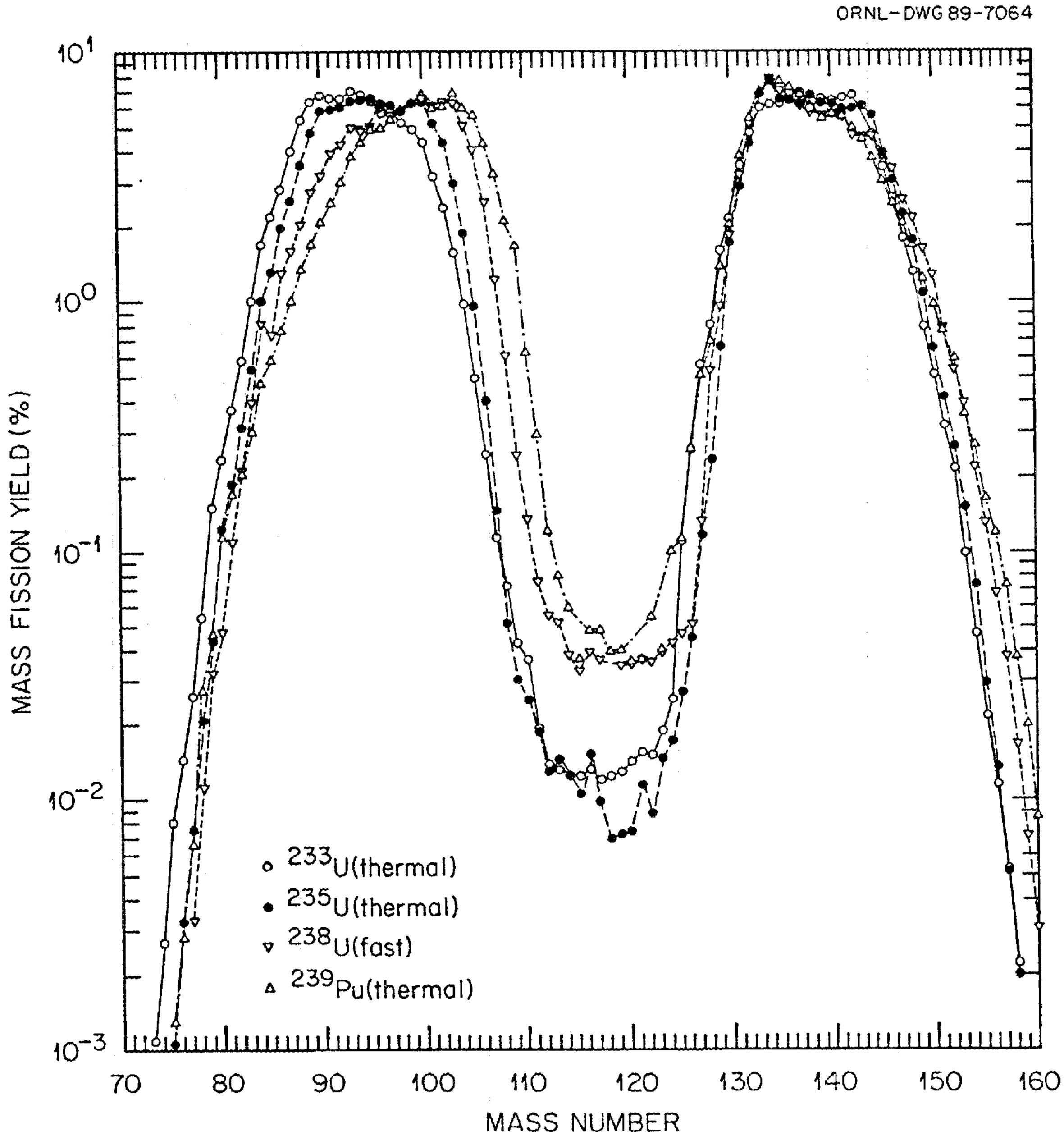

Figure 4. Distribution of fission fragments by yield and mass number. From I. B. Rider, 1981; and England, 1985.

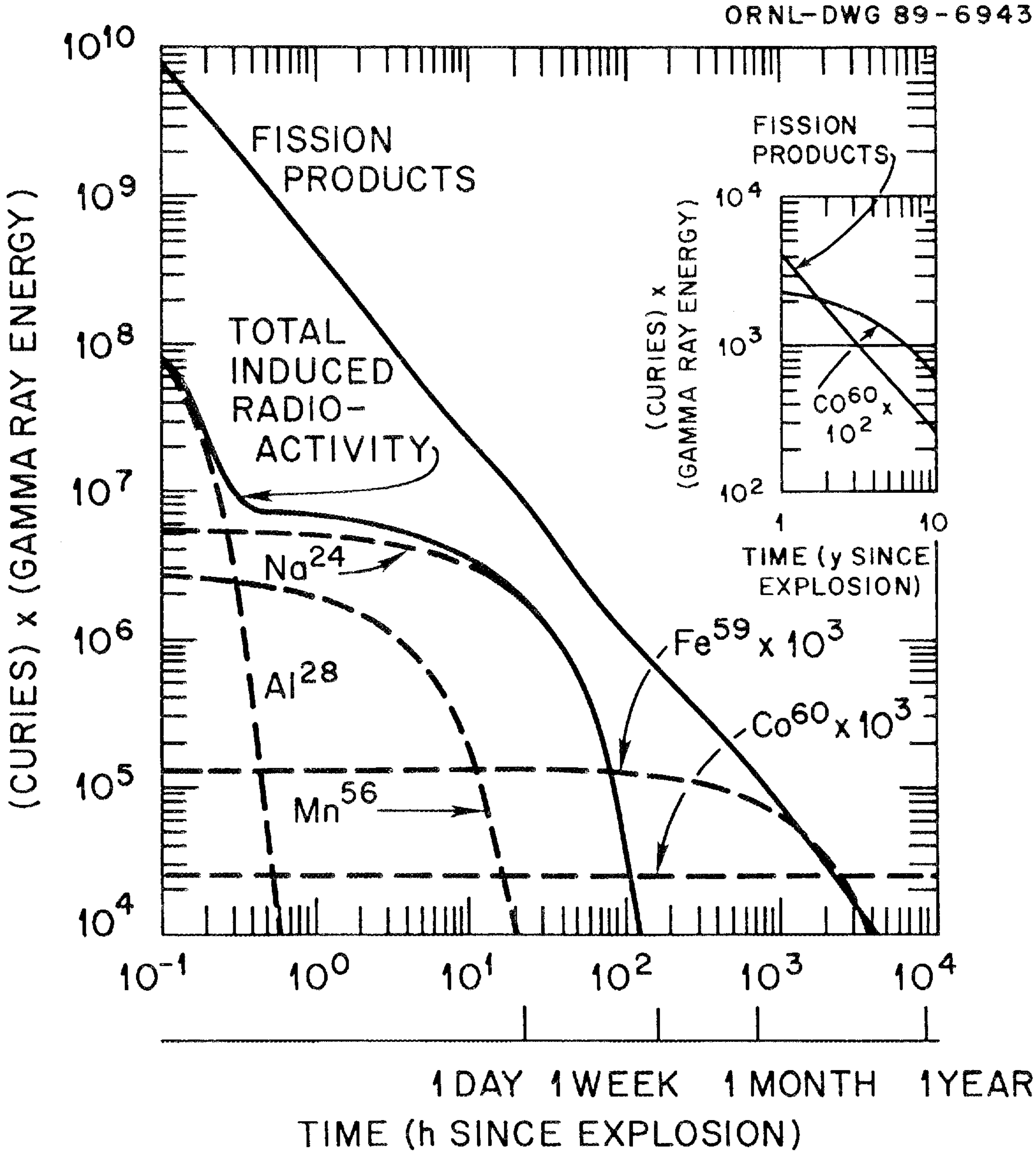

Figure 5. Comparison of induced radioactivity and fission product radioactivity from a 1–kt equivalent nuclear explosion. From Batzel, 1960.

However, there are two situations where induced radioactivity is stronger than fission product radioactivity: 1) a low air burst over materials that are susceptible to activation; and, 2) the period of about 20 hours to 2 weeks in and near the crater of a thermonuclear burst such as BRAVO.

A low air burst with a fireball that does not touch the ground will produce no residual radiation by fission fragments because they will all be carried up with the fireball. However, lethal levels of residual radiation could result from activation of nuclei in piles of salt or coils of copper cable that are irradiated by neutrons from the fireball. Table 1 lists some properties of radioactive isotopes that have fairly common parent elements and also have relatively high cross sections for neutron capture.

Some thermonuclear weapon designs use an exterior blanket of U^{238} surrounding an interior fission–fusion device to take advantage of the fission of U^{238} produced by fast neutrons from fusion (ENW77). Neutrons of appropriate energy from fusion can be captured by U^{238} to form U^{239} which decays (23.54 min half–life) to Np^{239}, which then decays (2.355 d half–life) to Pu^{239} (24065 y half–life). The resulting β and γ radiations from this decay scheme is considered to have a strong effect on the overall decay rate of radiation in the fallout from BRAVO through the first two days after detonation (Le85).

Unburned fissile materials in fallout can produce α and neutron radiations in addition to β and γ radiations. Neutron radiations in fallout are produced only by spontaneous fission of U^{238}. The unburned fissile elements usually have long half–lives, constitute only a tiny fraction of the mass of the debris, and are highly dispersed. Consequently, the β, γ, and neutron radiations from these sources are negligible compared to other sources in fallout. Alpha particles are not an external radiation hazard, but may cause long–term lung problems if their source is ingested (An75). A recent study by Levanon and Pernick (Le88) arrives at the conclusion that inhalation of fallout particles from ground bursts in the 0.5–kt to 10–Mt yield range does not constitute a serious radiological hazard.

TABLE 1

SOME PROPERTIES OF NEUTRON–INDUCED RADIOACTIVE ELEMENTS

Radioactive Isotope	Symbol	Half–life	Main Beta Energy (MeV)	Main Gamma Energy (MeV)	Parent Isotope	Parent Abundance (percent)	Cross–section (barns[a])
Aluminum	^{28}Al	2.2m	1.2	1.8	^{27}Al	100.	0.959
Chlorine	^{38}Cl	37.2m	2.2	2.2	^{37}Cl	24.2	0.202
Cobalt	^{60}Co	10.5m[b] and 5.3yr	1.5 0.3	1.3 1.3	^{59}Co	100.	48.5
Copper	^{64}Cu	12.7hr	0.6	1.3	^{63}Cu	69.2	4.48
Magnesium	^{27}Mg	9.5m	1.8	0.8	^{26}Mg	11.0	0.033
Manganese	^{56}Mn	2.6hr	2.8	0.9	^{55}Mn	100.	13.1
Phosphorus	^{32}P	14.3d	0.7	negl.	^{31}P	100.	0.14
Potassium	^{42}K	12.4hr	1.4	1.4	^{41}K	6.7	1.40
Silicon	^{31}Si	2.6hr	0.6	negl.	^{30}Si	3.1	0.303
Sodium	^{24}Na	15.0hr	0.6	2.8	^{23}Na	100.	0.691
Vanadium	^{52}V	3.8m	1.1	1.4	^{51}V	99.8	3.98
Zinc	^{65}Zn	244.4d	0.1	1.1	^{64}Zn	48.6	0.959

[a]one barn $= 10^{-24}$ cm^2.

[b]0.24 percent.

3. HOW FALLOUT IS PRODUCED

3.1 INTRODUCTION

A brief description of the sequence of events from ground-surface detonation to fallout is presented here. A visualization of these events will assist in understanding the physical processes involved in the formation of fallout. Such an understanding may be useful for the decision-maker in battle situations where troops may face the possibility of fallout from surface detonations.

The reader may have noted that the word "fallout" is used in two connotations. One usage applies to the process by which particles in the cloud from a nuclear fall to the ground, and the other applies to the particles after they have settled on the ground.

3.2 THE EARLY FIREBALL

When the fireball breaks through its enclosing structure, it will have a temperature ranging in the 10s to 100s of million degrees Kelvin, depending on the weapon design (ENW77). Solid materials at close range, out to a few meters radii for kiloton yield weapons, and several decameters for megaton-yield weapons, will be completely vaporized and reduced to the elemental ionized state. These ions will become thoroughly mixed with ions of fission fragments and elements used in the construction of the bomb, accelerating the cooling of the fireball. Within a few milliseconds after detonation the fireball will have expanded and cooled such that atoms will no longer be ionized due to thermal conditions.

Materials at greater radii will be reduced to the elemental state without being ionized, and at still greater radii, the materials will not be reduced to elemental form, but some (e.g., organic materials) may undergo changes in composition while others may be melted or vaporized. By this time in the history of a surface explosion, the fireball will have begun to rise and the shock wave will be forming.

3.3 FORMATION OF THE MUSHROOM CLOUD

Still further out, the shock wave will break up materials according to their mechanical properties, producing pulverized dust, chunks, rocks and slabs of various sizes. Additional dust, and materials smashed into larger granular form, will be carried up by the wind that is drawn in by low pressure underneath the rising fireball to form the stem of the mushroom. The heaviest materials will fall most quickly, some contributing to the lip of the crater. Radioactive particles in the stem may result from neutron activation of material outside the fireball or from heavy particles falling out from the fireball. These particles will contribute to stem fallout, which may contain about 10% of the total residual radioactivity for a surface burst, more for more deeply buried shots, and less for higher-altitude shots.

As the fireball rises, it will expand and cool. The combination of buoyant forces and drag forces with the ambient air will produce a rolling, toroidal motion of the outer portion of the cloud, with the outer surface rolling downward and inward

as the cloud rises. This action forms a doughnut with its axis along the stem of the mushroom, and having a cap rising up above the doughnut at the center. A photograph of a typical mushroom cloud formed by a low air burst at the Nevada Test Site is shown in Figure 6.

The rate of rise of the fireball will be faster for large yield weapons, and greatly dependent on local atmospheric conditions. The top of the cloud from a 1–Mt weapon surface detonation will reach an altitude (not the stabilized or final altitude) of about 3 miles (4.8 km) in 30 seconds (ENW77, p. 31), but for a 10–kt surface burst, it will require about 40–50 seconds (ENW77, p. 506).

The variability of maximum heights of nuclear clouds is indicated in Figure 7 as a function of weapon yields (OCD70). The variability in the height depends on atmospheric conditions and on the amount of heavy materials taken up by the fireball. We may take the top line to represent the top cloud height for clouds from near–surface bursts in which additional solids or liquids have not been incorporated. Figure 8 shows the altitudes of the tops and also the bottoms of the stabilized cloud heights as a function of yield (ENW77, p. 431). The top altitude in Figure 8 is just below the mean cloud top shown in Figure 7.

3.4 FORMATION OF THE FALLOUT CLOUD

The fireball will cease to rise when it has cooled sufficiently to have the same density as the ambient air. Below the tropopause, the temperature of the atmosphere decreases with increasing altitude, as illustrated in Figure 1. For yields greater than about 30 kt, depending on local conditions, the top of the cloud will reach the stratosphere, where the temperature increases with increasing altitude. Consequently, the rate of rise in the stratosphere will decrease, and the rate of lateral spread will increase rapidly.

Local winds will now begin to affect the shape and movement of the fallout cloud. Surface winds are not a reliable indicator of where the fallout will be deposited. Winds may have different directions and speeds at different altitudes. For those close enough to observe the mushroom cloud, these wind variations may be observed by their affect on the fallout stem. Observation of the movement of the fallout cloud, if possible, will give a good indication of where the fallout may be headed.

If many megaton–yield warheads have been detonated within an area of a few hundred square kilometers, it may be surmized that winds within the area will be entirely changed due to the sudden influx of enormous quantities of energy. Winds surrounding the area, possibly out to several hundred kilometers, may also be affected. These factors complicate attempts to predict where fallout will be deposited.

3.5 THE FALLOUT PROCESS

Within about 10 minutes for 10–kt detonations and about 15 minutes for 1–Mt, the fallout cloud will reach its stabilized height and size, and all major chemical transformations will have occurred. Minor transformations will continue to occur due to transmutation of the fission fragments by radioactive decay.

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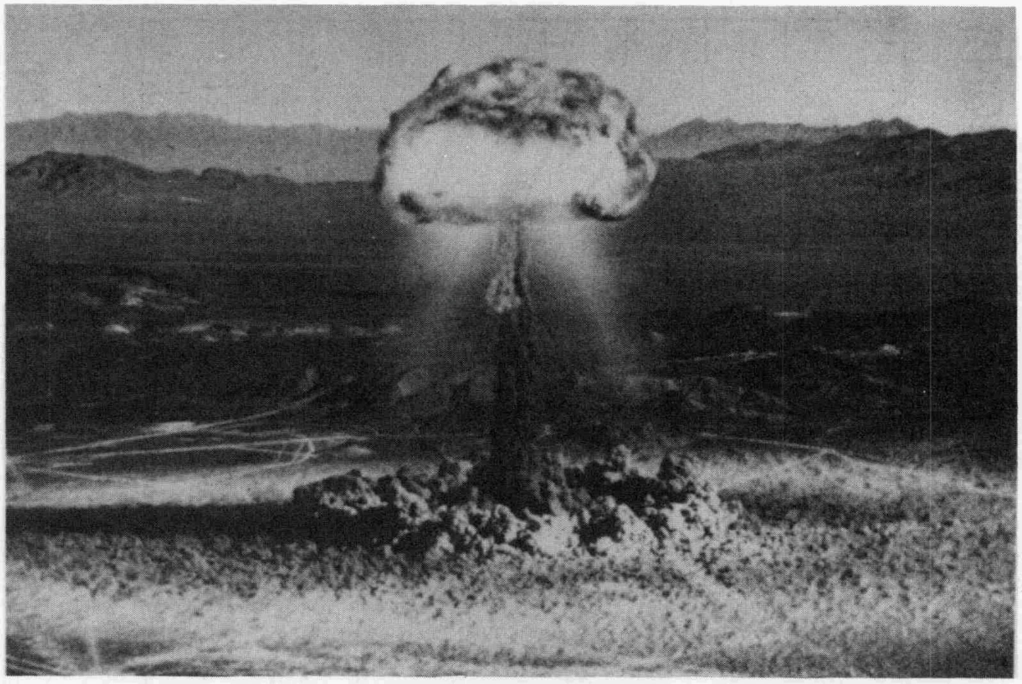


Figure 6. Mushroom cloud produced by a low altitude air burst at the Nevada Test Site.

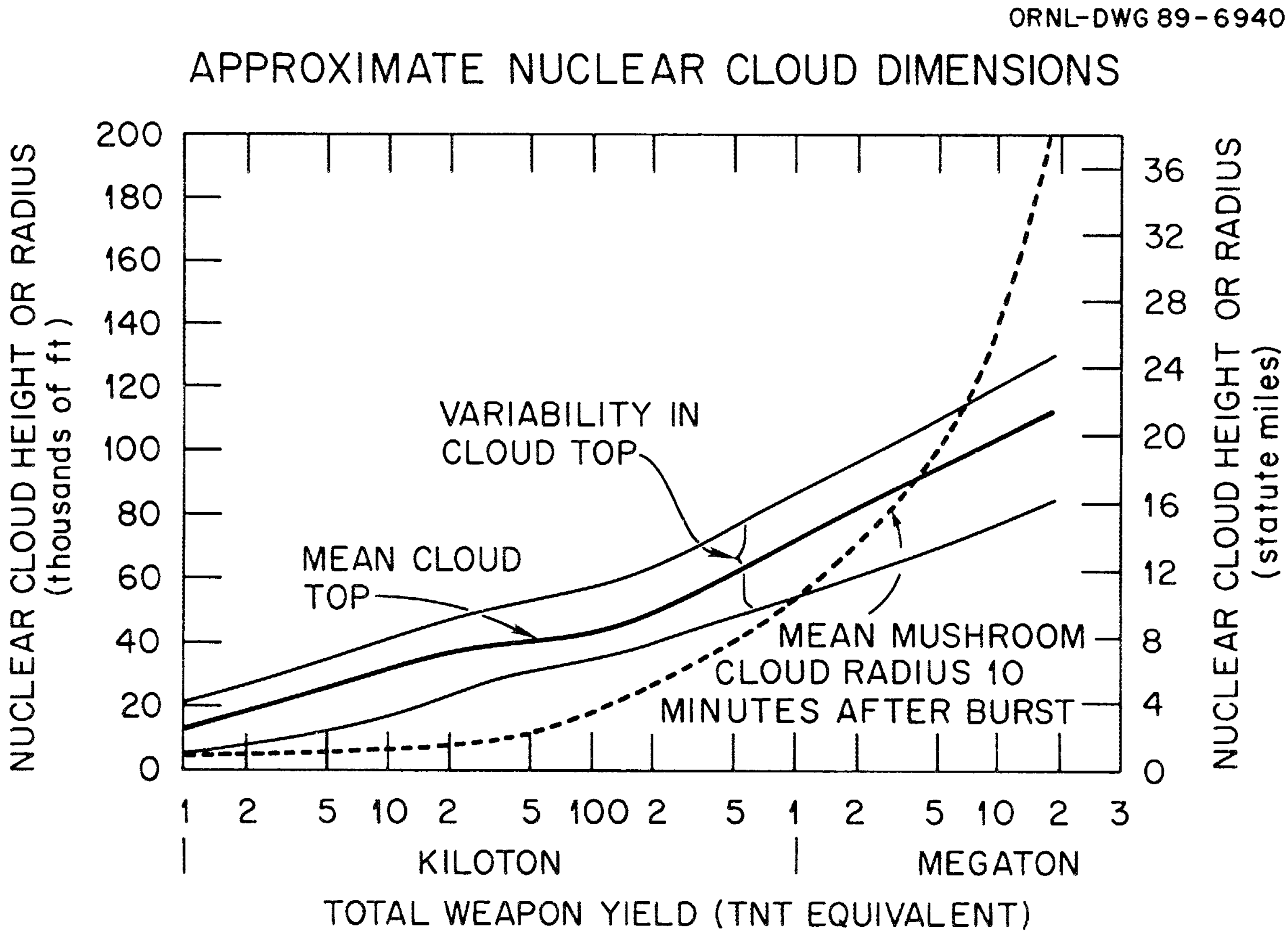


Figure 7. Approximate height of top and radius of nuclear cloud as a function of yield. From Office of Civil Defense, 1970.

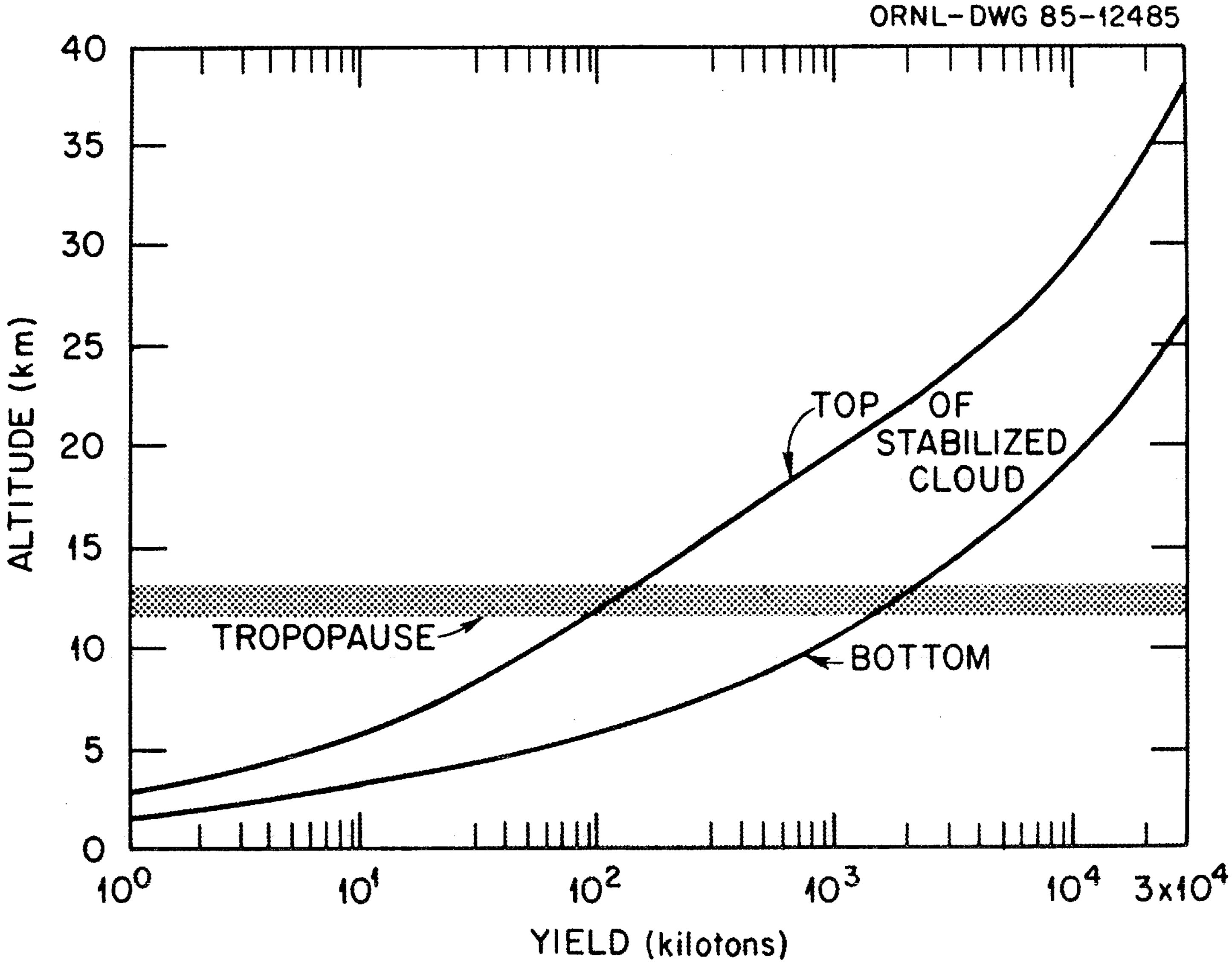


Figure 8. Height of top and bottom of nuclear cloud as a function of yield. From Glasstone and Dolan, 1977.

The cloud will now move laterally according to local winds, and will continue to expand by diffusion. As it moves, the larger and heavier particles will fall to earth to produce local fallout. The fall of particles in the atmosphere depends, among other things, on the air density; a particle that may have an appreciable fall speed at 80 km altitude may essentially float at 20 km (By65).

The downward speed, called the terminal velocity, is reached when the downward force (gravity less buoyancy) is balanced by the resistive force of the air. The resistive force is proportional to the cross-sectional area of the particle presented to the air in the direction of travel, its drag coefficient, the density of the air, and to the velocity raised to a power between one and two, depending on the velocity of the particle relative to the air (Bi60). The fall times shown in Figure 9 are for *perfect spheres* with a density of 2 gm cm^{-3}, corresponding to the average density of fallout particles from ground-surface bursts (Cr66). The lines are curved because of the decrease in air density with altitude.

Particles with shapes illustrated in Figures 2 and 3 will take longer to fall than the times shown in Figure 9 because their drag coefficients will be larger than that of a perfect sphere (unity), due to surface roughness and irregular shape. Consequently, nonspherical fallout particles will be carried further downwind than smooth spherical particles, and will, therefore, be more greatly dispersed across the country, resulting in lower local radiation intensities for a given yield.

As the particles fall through the atmosphere, they may be accelerated or decelerated laterally by local winds according to the resistive force described above. Smaller particles will be accelerated very quickly up to speeds that nearly match the lateral wind speed, whereas larger, heavier particles may reach the ground without being significantly affected by local winds. As a result, smaller particles may have a considerably greater spread on the ground than the larger particles.

To simplify dealing with winds that vary in speed and direction with altitude, the "effective wind" has been defined to be the mean of two average winds, 1) the horizontal wind averaged from the ground to the base of the stabilized fallout cloud, and 2) the horizontal wind averaged from the ground to the top (ENW77, p. 423). The average winds may be determined by measurements on a rising balloon, or they may be roughly estimated by observations of the stem of the mushroom cloud.

Stem fallout will be the first fallout to be completed, and may reach completion within less than a half hour after detonation (Mi69). Further downwind, the first fallout may not begin for times of a half hour to several hours after detonation, depending on the distance downwind, the speed of the fallout cloud, and the effective winds. After fallout begins to arrive at an area, fallout may continue to arrive for periods varying from 2 to 20 hours, depending on the distance downwind and the yield of the detonation. Fallout duration from BRAVO (15 Mt) was estimated to be 5 h at 150 km downwind, and 7 h at 210 km downwind (Le85).

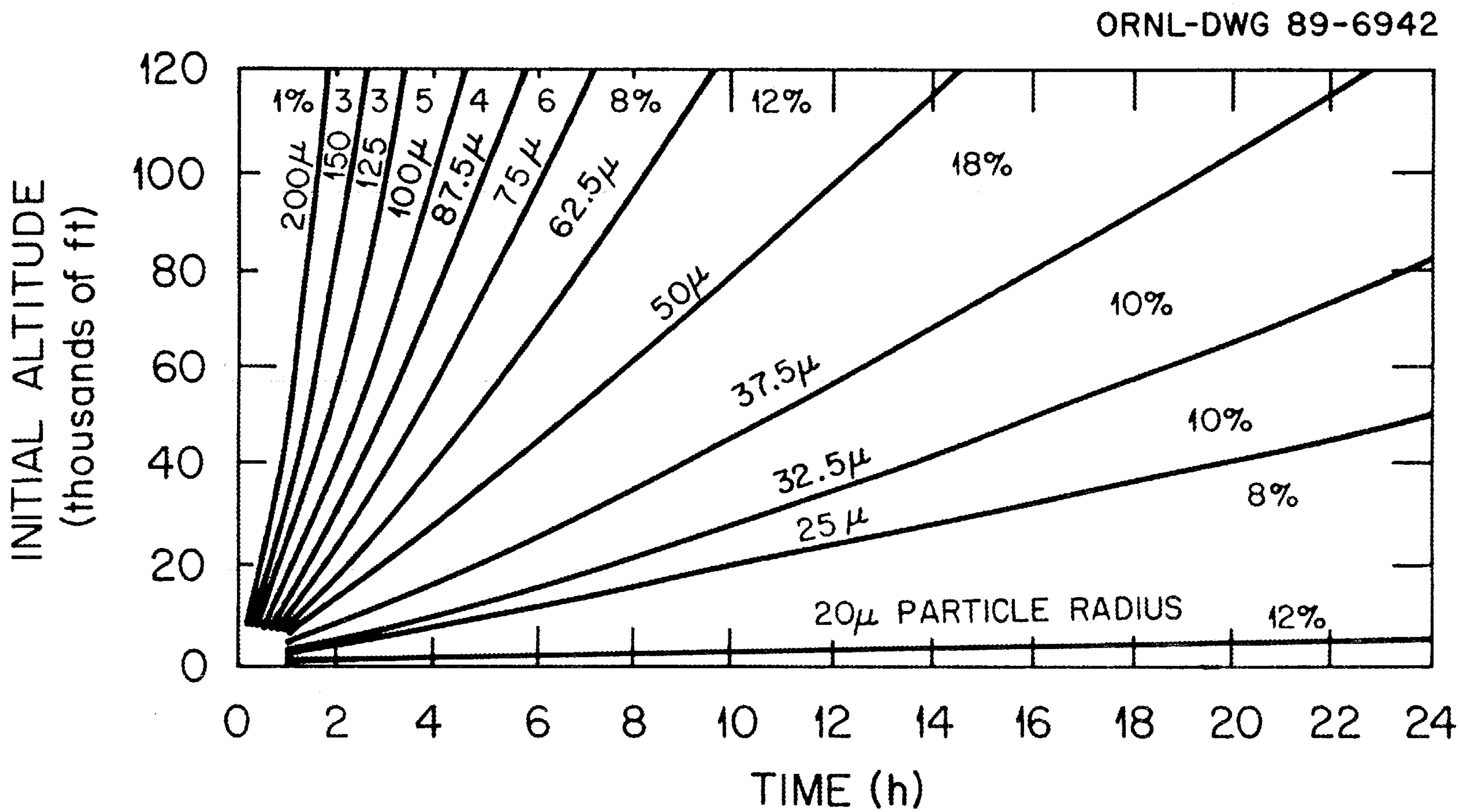


Figure 9. Fall times of smooth, spherical particles from various altitudes, and percentages of total activity carried. From Office of Civil Defense, 1970.

4. FACTORS AFFECTING FALLOUT PRODUCTION

4.1 INTRODUCTION

Factors affecting the quantity and characteristics of fallout are 1) the height of burst, 2) the nature (liquid or solid) and chemical composition of the external materials affected by the fireball, 3) the yield or size of the warhead, 4) the design of the warhead and container, and 5) atmospheric conditions. In many situations, all of these factors are interrelated, as will be seen in the following discussions.

4.2 HEIGHT OF BURST

If the warhead is detonated in the air such that the fireball does not affect any external solids or liquids, there will be no local fallout, with one possible exception. If the yield is so low that the bottom of the fallout cloud reaches its maximum height within the troposphere, then the possibility exists for weather phenomena to bring radioactive materials to the ground within the local area, such as the partial rainout which occurred in the vicinities of Hiroshima and Nagasaki.

The altitude of the tropopause (the top of the troposhere), as indicated in Figure 1, may vary from 7 to 17 km (23 to 56 kilofeet) (Ir80). Most weather phenomena occurs below the tropopause, hence we may conclude, with the aid of Figure 8, that partial local rainout is a possibility for low altitude airbursts with any yield up to about 4 Mt, depending on the existing altitude of the tropopause.

If a warhead is detonated above an area containing high–rise structures such as skyscrapers, grain elevators, or TV broadcast antennas, the height of burst may be such that portions of these structures may be vaporized without the fireball touching the ground. The chemical composition of fallout from such a burst may be different than that of fallout from a ground burst, containing calcites from vaporized concrete, and possibly resembling the BRAVO fallout particles shown in Figure 3.

Suppose the height of burst of a weapon of given yield is gradually decreased from zero height where the fireball just touches a flat ground surface to a negative height corresponding to a deep underground detonation. The production of prompt (early or local) fallout as a function of height of burst can be estimated from Figure 10 (No64). In this figure, a negative value of the abscissa (ratio of depth of burst/depth of apparent crater) indicates that the burst is ABOVE ground. When the abscissa is -1, the height of burst above ground is approximately half the fireball radius. In this case, the resultant total release of radioactive materials is equally divided between local (prompt) and delayed (long term airborne) fallout.

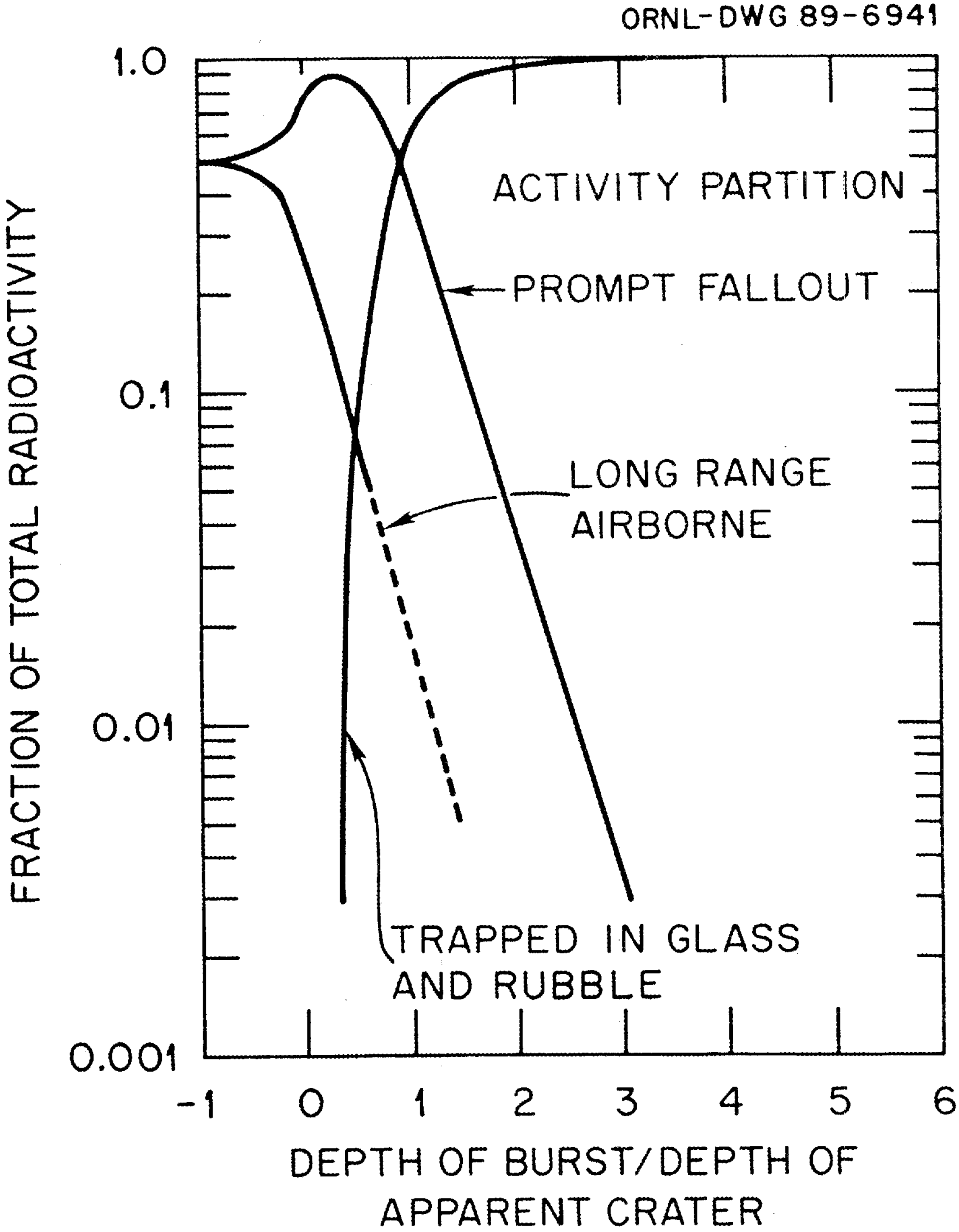


Figure 10. Radioactivity release as a function of ratio of depth of burst to depth of apparent crater. An apparent crater is the crater that is seen visually following the detonation; a true crater is the crater geometry immediately after the detonation, before fallback or inflow processes occur. From Nordyke and Wray, 1964.

The fraction of prompt fallout rises to about 80% when the height of burst is reduced to zero (abscissa in Figure 10 is zero) and reaches a maximum of 90% for slightly buried detonations. When the depth of burst is almost equal to the depth of the apparent crater, almost half the total radioactivity produced is trapped in the glass and rubble in the crater. When the depth of burst is more than twice the depth of the apparent crater, hardly any radioactivity escapes, being trapped almost entirely within the crater.

In summary, there will be no local fallout of fission products if the fireball does not touch the ground or a high structure, providing there is no rainout. There will also be no local fallout if the warhead penetrates the earth at least two apparent crater depths before detonating, the depth depending on the yield. There will be maximum local fallout if the warhead is detonated just below the surface.

4.3 CHEMICAL COMPOSITION OF AMBIENT MATERIALS

The effect of two types of ambient materials (steel and coral) on the chemical composition of fallout has been discussed above. For a ground–surface burst, the mass of solids in the crater that is vaporized far exceeds the mass of the warhead and its container, hence the chemistry of the fallout is dominated by the vaporized materials from the crater. The chemical composition of ambient materials affects fractionation processes and also determines the physical characteristics of the fallout particle. Variations in particle size, shape and density will affect the rate of descent and the distance the particles are transported horizontally by local winds. As discussed above, a slower descent will result in greater dispersion of the fallout particles. Hence the chemical composition of materials vaporized by the fireball has a significant effect on the intensity of radiation from fallout.

4.4 YIELD OF WARHEAD

The volume of solid material in a fallout cloud is roughly proportional to the yield for ground–surface bursts. The greater energy released by the larger yields will carry these solids to greater height, with the consequence that fallout is spread out over a larger area.

An indication of the dependency of the extent and intensity of fallout with yield is given in Table 2, which gives scaling relationships for unit–time reference dose-rate contours for an *idealized* fallout pattern for a contact surface burst and a 15 mph effective wind. These relationships will be discussed in greater detail under "Patterns of Fallout Deposition and Areal Extent."

4.5 WEAPON DESIGN

Four types of weapons and their effect on fallout will be briefly discussed: 1) pure fission; 2) enhanced neutron radiation (mostly fusion); 3) boosted (mostly fission, some fusion); and 4) fission–fusion–fission (conventional thermonuclear, 50/50 fission/fusion). The yields of the first three types are usually considerably less than megaton range, while the last type usually is in the near megaton or greater range (ENW77). For ground surface bursts, *all of the same yield*, the pure fission

TABLE 2

SCALING RELATIONSHIPS FOR IDEALIZED UNIT–TIME REFERENCE DOSE–RATE CONTOURS FOR A CONTACT SURFACE BURST WITH A TOTAL YIELD OF W KILOTONS, 50% FISSION, AND A 15 MPG EFFECTIVE WIND [Taken from the Effects of Nuclear Weapons (Gl77)]

Reference dose rate (rads/hr)	Downwind distance (statute miles)	Maximum width (statute miles)	Ground zero width (statute miles)
3,000	0.95 $W^{0.45}$	0.0076 $W^{0.86}$	0.026 $W^{0.58}$
1,000	1.8 $W^{0.45}$	0.036 $W^{0.76}$	0.060 $W^{0.57}$
300	4.5 $W^{0.45}$	0.13 $W^{0.66}$	0.20 $W^{0.48}$
100	8.9 $W^{0.45}$	0.36 $W^{0.60}$	0.39 $W^{0.42}$
30	16 $W^{0.45}$	0.76 $W^{0.56}$	0.53 $W^{0.41}$
10	24 $W^{0.45}$	1.4 $W^{0.53}$	0.68 $W^{0.41}$
3	30 $W^{0.45}$	2.2 $W^{0.50}$	0.89 $W^{0.41}$
1	40 $W^{0.45}$	3.3 $W^{0.48}$	1.5 $W^{0.41}$

weapon will produce the greatest radioactivity in fallout, boosted will be second, fission–fusion–fission will be third, and the enhanced neutron weapon will produce the least radioactive fallout.

The 50/50 fission/fusion weapon must have almost twice the yield to produce the same amount of residual radioactivity as the pure fission weapon. In this case, the top of the stabilized cloud from the 50/50 fission/fusion weapon would rise about a mile or so higher, as indicated by either Figure 7 or 8) than the cloud from the pure fission weapon having half the yield, causing the fallout to be more dispersed.

For low airbursts of the same yield, the enhanced neutron warhead will produce the greatest amount of residual radiation, due to neutron activation.

4.6 ATMOSPHERIC CONDITIONS

The most significant atmospheric factor affecting the distribution and intensity of fallout radiation on the ground is the pattern of local winds in the atmosphere. Effective wind speeds may range from nearly zero to 100 kilometers per hour, depending on season, locality, and time of day. High effective wind speeds will result in long narrow deposition patterns. These patterns may be distributed over a greater area, and therefore produce lower radiation intensity, than when the fallout is produced in an area of low effective wind speeds, because the aerodynamic forces resulting from particle–wind interactions will sustain the flight of some shapes of fallout particles. If the fallout originates near the center of a cyclonic weather pattern, the fallout may be very intense in the local region due to low effective wind speeds and circulating weather patterns.

High humidity in the air will usually result in rain after a nuclear burst. The fireball will carry wet air trapped within it to higher altitudes where the fireball cools and the water condenses out to form rain. For low–yield bursts, under a megaton, the fireball rise may stabilize at an altitude such that part of the nuclear cloud is within the rain cloud. In this case, the scavenging process by which radioactive debris is removed from the portion of the nuclear cloud within the rain cloud is called "rainout" (ENW77, p. 418). Rains that fell after the Hiroshima and Nagasaki bombings were called "black" rain, because the drops were black like dirty oil, probably carrying some fallout and smoke particles from the fires that were started by the weapons (CCMD81). These cases are discussed further in Section 7.6.

4.7 HOW MUCH RADIOACTIVE DEBRIS COMES DOWN AS LOCAL FALLOUT?

Estimates have been made on the fraction of radioactive debris that is deposited locally from various weapon tests by using the following equation:

$$K_m = 1/W_f \sum_{i=1}^{i=N} I_i dA_i \qquad (1)$$

in which K_m is the K-factor (also called normalization factor) based on field measurements, W_f is the yield due to fission, dA_i is a surface area element

(usually irregular) over which the radiation intensity, *extrapolated* from the measured intensity back to time H+1 hr, is fairly uniform at some level I_i (measured in R/hr), and N is the number of such surface elements such that the sum of them is A_L, the area defined as being affected by local fallout.

The concept of determining this important ratio and discussions of measurements and results are described in ENW77, pages 453–456, and in greater detail in DCPA Research Report No. 20 (NAS73). In the latter report, results from 25 weapons tests are tabulated, out of which 5 were selected and *averaged* to estimate K_a. These 5 cases included two greatly different types of nuclear detonations, involving greatly differing chemical compositions in the materials taken up with the fireballs and differing atmospheric conditions. The two types of nuclear detonations were 1) three small yield fission devices over dry desert soil and 2) two multimegaton thermonuclear devices over sand, coral, and sea water. The basis for selection of these 5 cases was not described. Variations among independent measurements of K_m tabulated for each of the 5 selected weapon tests ranged up to 94% between maximum and minimum. Some possible causes of these variations were discussed generally but not specifically. In all cases, the radiation intensity measurements were extrapolated back to the time H+1 by assuming a decay according to $t^{-1.2}$, whereas a decay according to $t^{-1.4}$ may have been more accurate in some or all of the cases, for reasons discussed in Section 6.2.

A value of $K_a = 1930$ was obtained from the averaging process described briefly above, from which, using a value of $K_t = 2900$ (ENW77; NAS73) (this value was *averaged* between U–235 and Pu–239 fission sources), it was estimated (ENW77) that about 60% (actually about 2/3) of the radioactive debris from groundbursts will be deposited locally. The value of 1930 is used widely in fallout models (Po66; Pu59), and the value of 60% deposited locally has been used to indicate that 40% will be distributed in world–wide fallout following a nuclear war (Br86; Kn83). The SIMFIC fallout model (No79b) allows the input of seven different K-factors according to the weapon design.

From the brief review given here it should be apparent that the determination of the fraction of fallout deposited locally needs careful review and reevaluation. Only one of the several factors mentioned above would increase the value of K_a by 64%, namely, extrapolation from H+12 to H+1 hr with $t^{-1.4}$ rather than $t^{-1.2}$. In addition, the theoretical value of K_t should be redetermined using modern cross-section data, and the specific K_t corresponding to a specific fission source should be used.

5. PATTERNS OF FALLOUT DEPOSITION AND AREAL EXTENT: STANDARD DECAY

Because of all the various factors affecting the deposition of fallout, as described in the preceding paragraphs, it is not surprising that actual fallout patterns are highly irregular, as illustrated in Figure 11. In addition to these large-scale irregularities, local "hot spots" may exist due to fallout particles accumulating in piles formed by wind motion or water currents from rainfall.

Idealized patterns, as illustrated in Figure 12, in combination with the scaling relationships given in Table 2, are useful for rough estimation of the possible extent that could be affected by harmful radiation. Because radiation from fallout decays rapidly with time, the contour for a given radiation level will shrink with time. These patterns and relationships are given for the time of one hour after detonation, at which time most fallout particles, except for yields under about 10 kt, have not yet settled to the ground. This time, called "unit-time," is for reference purpose only.

The unit-time reference dose-rate is the exposure rate in Roentgens/hr that would be measured at the location specified if all the fallout that is going to come down at the location is already in place at one hour after detonation. For most weapons, most of the fallout will still be in the air at one hour after detonation. The unit-time concept is useful if all fallout decays according to a simple decay law such as $t^{-1.2}$, because, once the unit-time reference exposure rate is determined for an area, the exposure rate for undisturbed fallout at the location can be determined for a future time by using the decay law. The so-called "standard" decay equation is

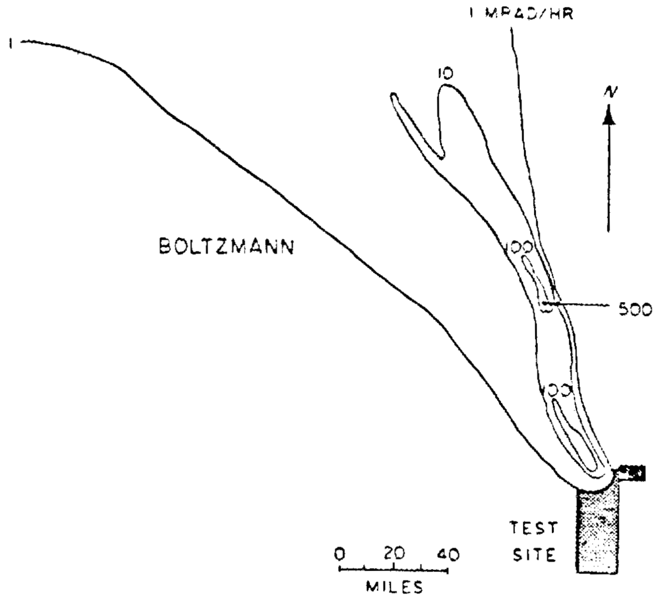
$$R = R_o t^{-1.2} \qquad (2)$$

in which R is the estimated dose-rate at the time t in hours after the detonation, and R_o is the unit-time reference dose-rate. Values of R_o for idealized fallout patterns may be obtained from either Figure 12 or Table 2.

A simple approximation for the "standard" decay is given by the "seven-ten" rule: for every multiple of seven of the time, t, in equation (2), the dose-rate R will decay by a factor of 10.

Note that, in Table 2, the scaling relations change for maximum width and ground zero width for the idealized fallout pattern for the different dose-rate contours, but for the distance downwind, the scaling relationship remains constant, and may be simply approximated by the square root of the yield.

As we shall see, fallout does not decay according to a simple decay law, even when undisturbed by wind or rain. However, Table 2 is useful to give an indication of relative extent and intensity of fallout as a function of yield, even though idealized.



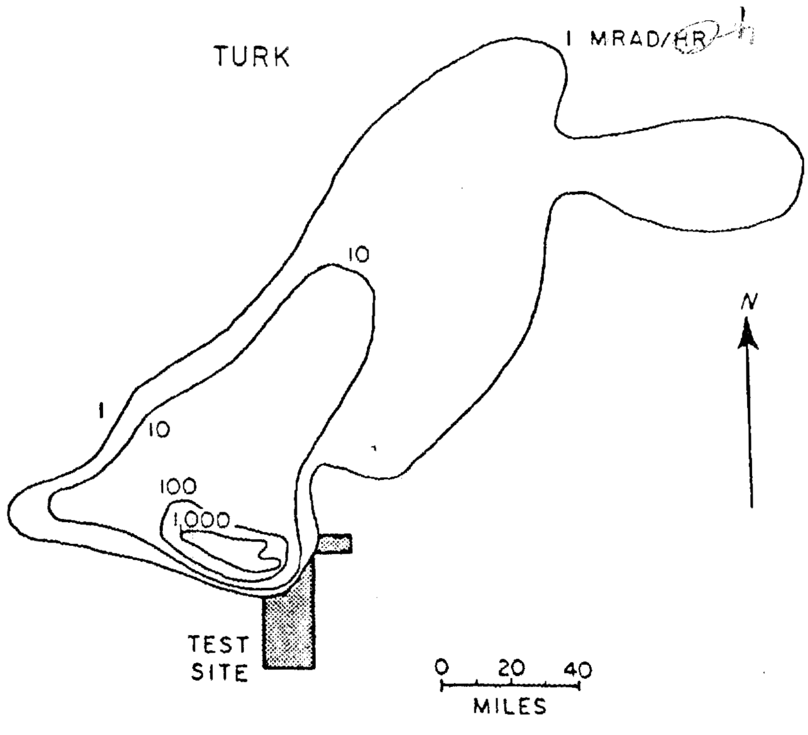


Figure 11. Early fallout dose-rate contours from shots BOLTZMANN and TURK at the Nevada Test Site. From The Effects of Nuclear Weapons, 1977, p. 421.

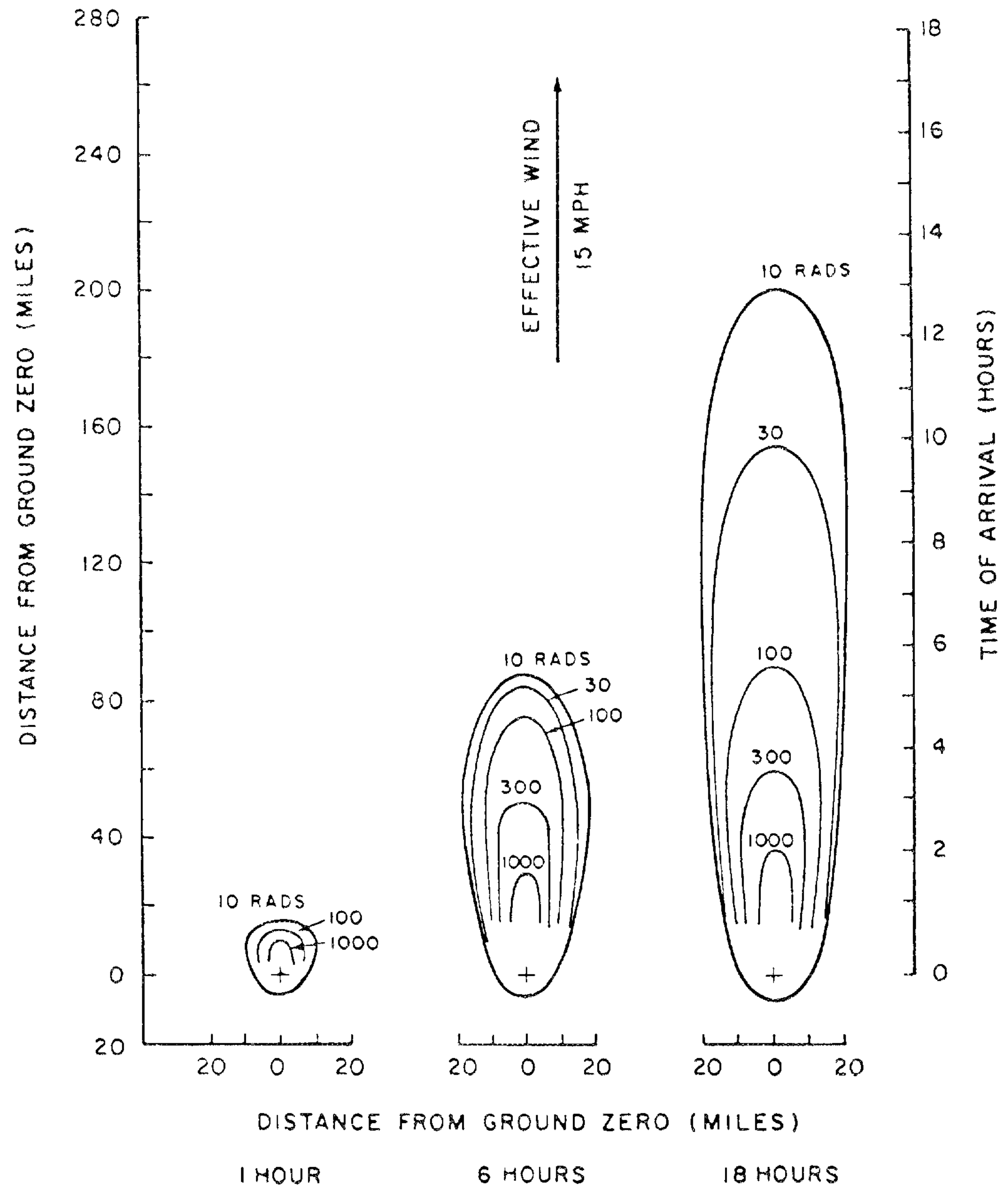


Figure 12. Idealized unit–time dose–rate patterns for early fallout from a surface burst. From The Effects of Nuclear Weapons, 1977, p. 429.

6. CHARACTERISTICS OF RADIATION FROM FALLOUT

6.1 ENERGY SPECTRA

In a nuclear detonation, more than 300 radioactive isotopes are produced by fission and by neutron activation. Each of these have different decay schemes, involving a wide range of half-lives and energies of the emitted βs and γs. Half-lives may range from microseconds to millions of years. Energies of βs in fallout may range from 0.025 to 10 MeV, with the majority of them being in the vicinity of 1 MeV. Energies of γs range from 0.001 to 11 MeV, but the ones of primary concern have energies between 0.1 and 5 MeV.

Because of the great number of contributing isotopes with their wide range of half-lives, the energy spectrum of the radiations emitted from fallout will change with time. Figures 13 through 16 illustrate γ spectra for different times after detonation, at 1, 4, 24, and 48 h, produced by unfractionated fission products and actinides from a hypothetical 10 MT U^{235} fission warhead, based upon recent data for fission and decay products incorporated in the ORIGEN S model (He88). Photons from actinides account for less than 5% of the total. The illustrated spectra include radiations from volatile components, which would not be present in fallout on the ground. The range of energy of emitted γs from 0 to 6 MeV has been split into 50 boxes of equal energy, 0.2 MeV per box, rather than showing a logarithmic splitting of the spectrum as often done (Ne59; We58).

Note that at 1 h (Figure 13) there are significant radiations with energy between 2–4 MeV. At 24 h (Figure 15), the radiations with energies over 3 MeV have become insignificant. In general, the mean energy per photon from fission fragments will decrease from around 0.85 Mev during the first few hours to 0.5–0.6 MeV for the period from about 40 to 10,000 h (Sp80). Energy spectra are discussed in considerable detail in *Structure Shielding Against Fallout Gamma Rays from Nuclear Detonations* (Sp80).

Fractionation processes dependent on the chemical composition of materials vaporized by the fireball can change both the time and location dependence of the energy spectrum. Fusion processes which induce the presence of Np^{239} and U^{237} may also change the shape of the photon energy spectra during the first day or two after the detonation.

6.2 RATE OF DECAY OF GAMMA RADIATION

The multiple radioisotopes in fallout, with their widely varying half-lives, produce a complex pattern of decaying intensities as time goes on after detonation. From the spectra shown in Figures 13 through 16, the rate of decay from 1 h to 48 h for the γs in the energy range of 0–0.6 MeV is well represented by $t^{-1.2}$, but the radiation in the 0.6–0.8 MeV bin decays as $t^{-1.09}$, and in the 2.6–2.8 MeV bin it decays as $t^{-1.96}$. Although the radiation decay of each radioisotope is exactly given by an exponential decay law, the resultant radiation decay of several

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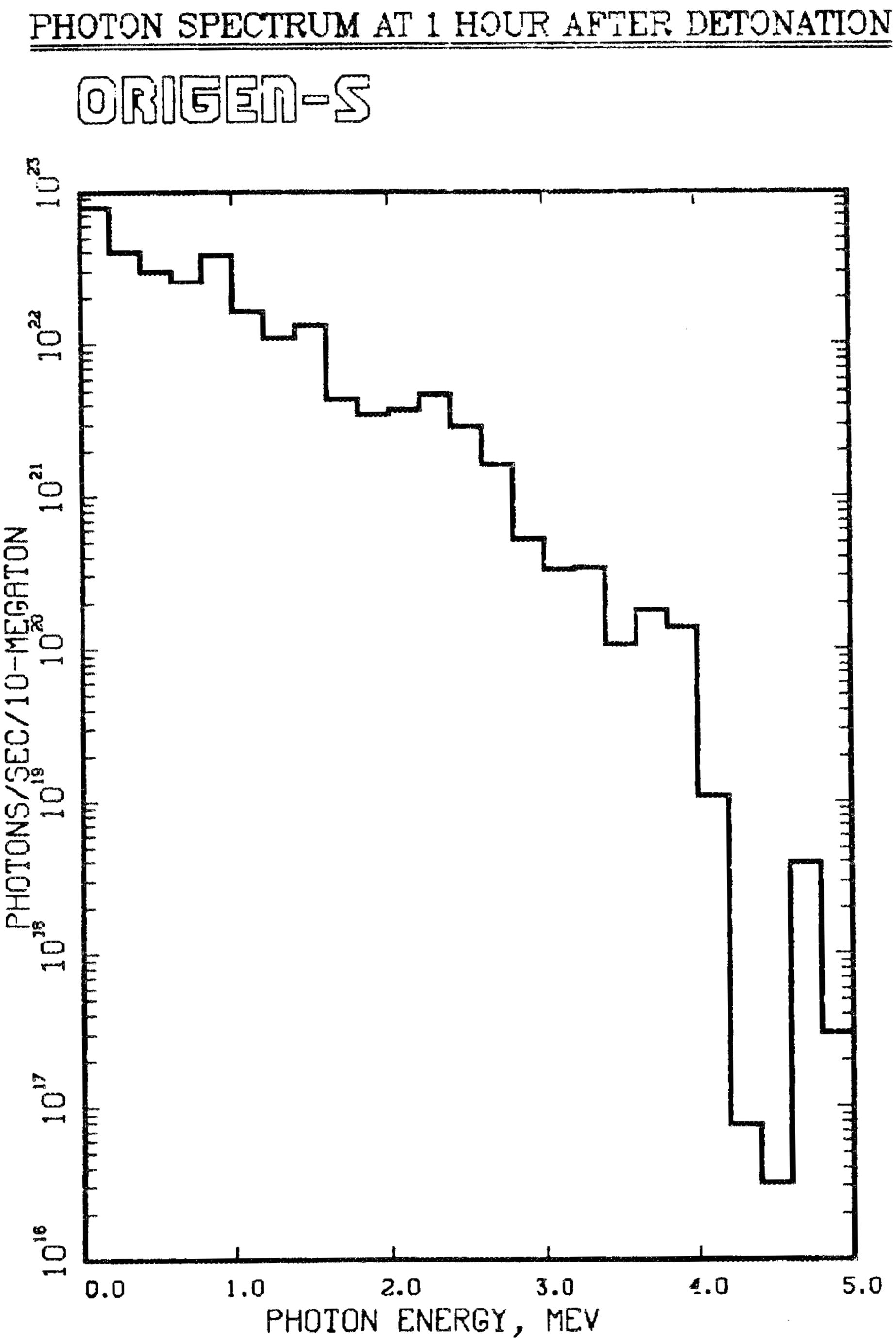

Figure 13. Theoretical evaluation of the gamma energy spectrum from fission products from a hypothetical 10 MT U^{235} warhead, at 1 h after detonation. From Hermann, 1988.

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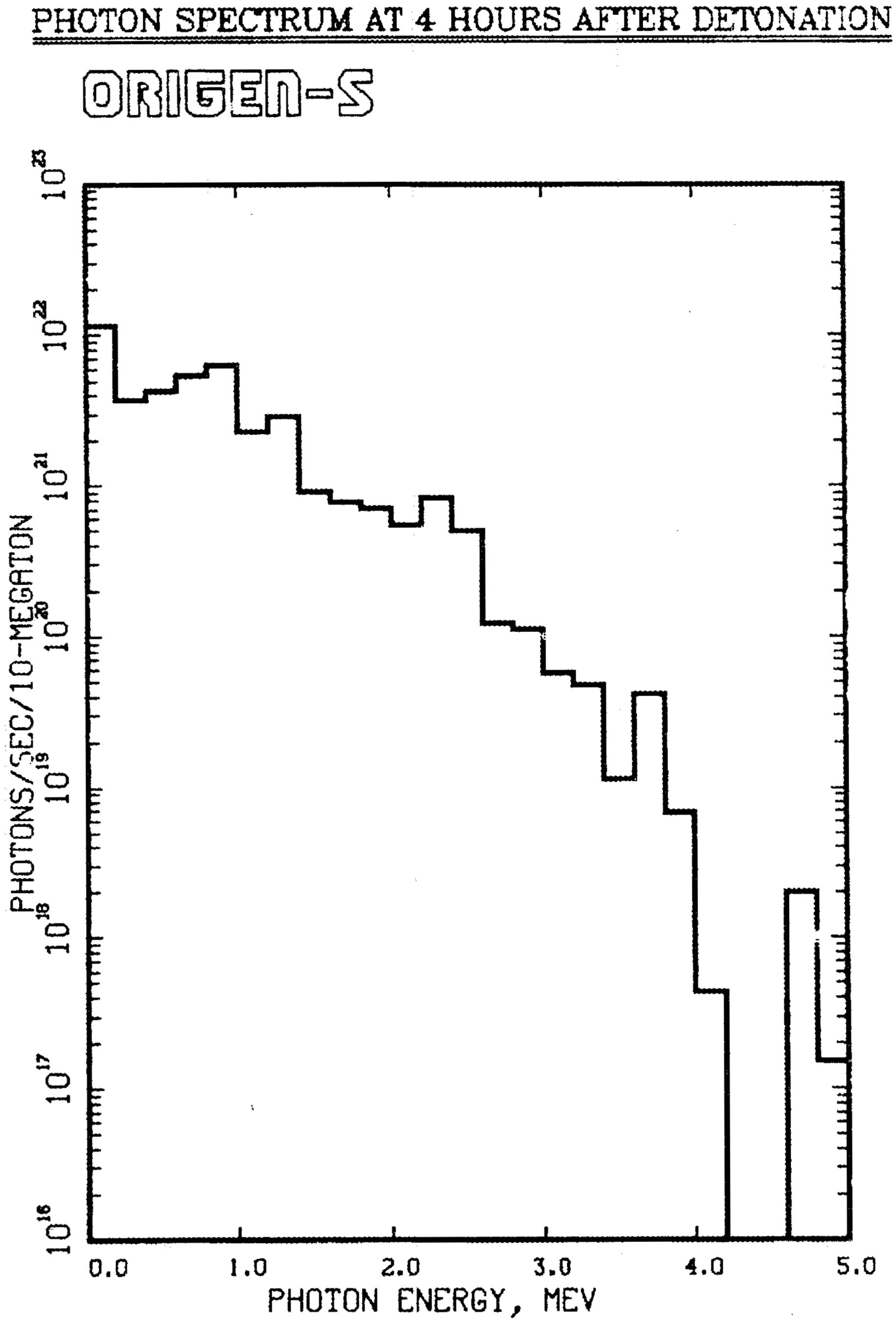

Figure 14. Theoretical evaluation of the gamma energy spectrum from fission products from a hypothetical 10 MT U^{235} warhead, at 4 h after detonation. From Hermann, 1988.

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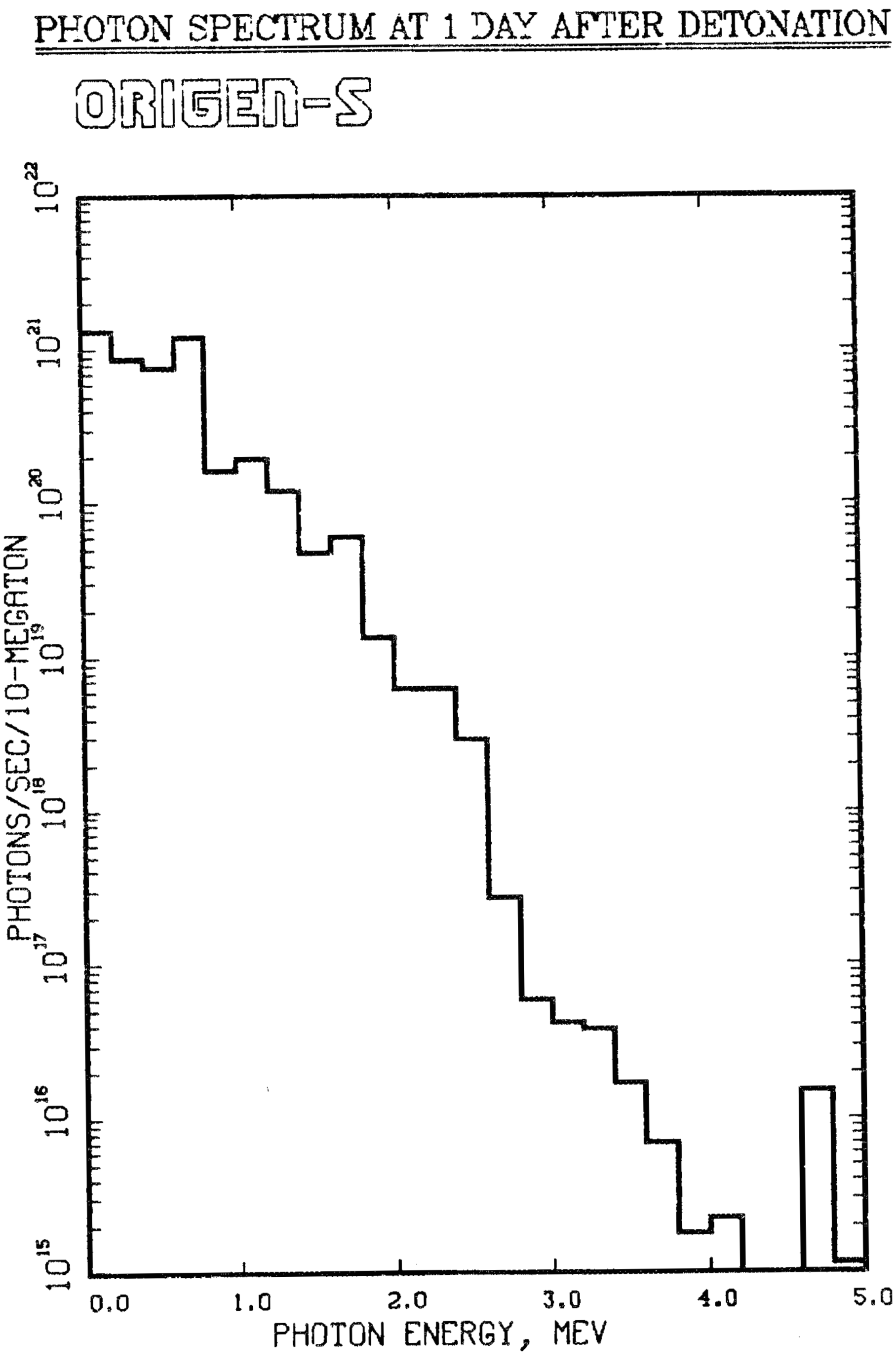

Figure 15. Theoretical evaluation of the gamma energy spectrum from fission products from a hypothetical 10 MT U^{235} warhead, at 1 d after detonation. From Hermann, 1988.

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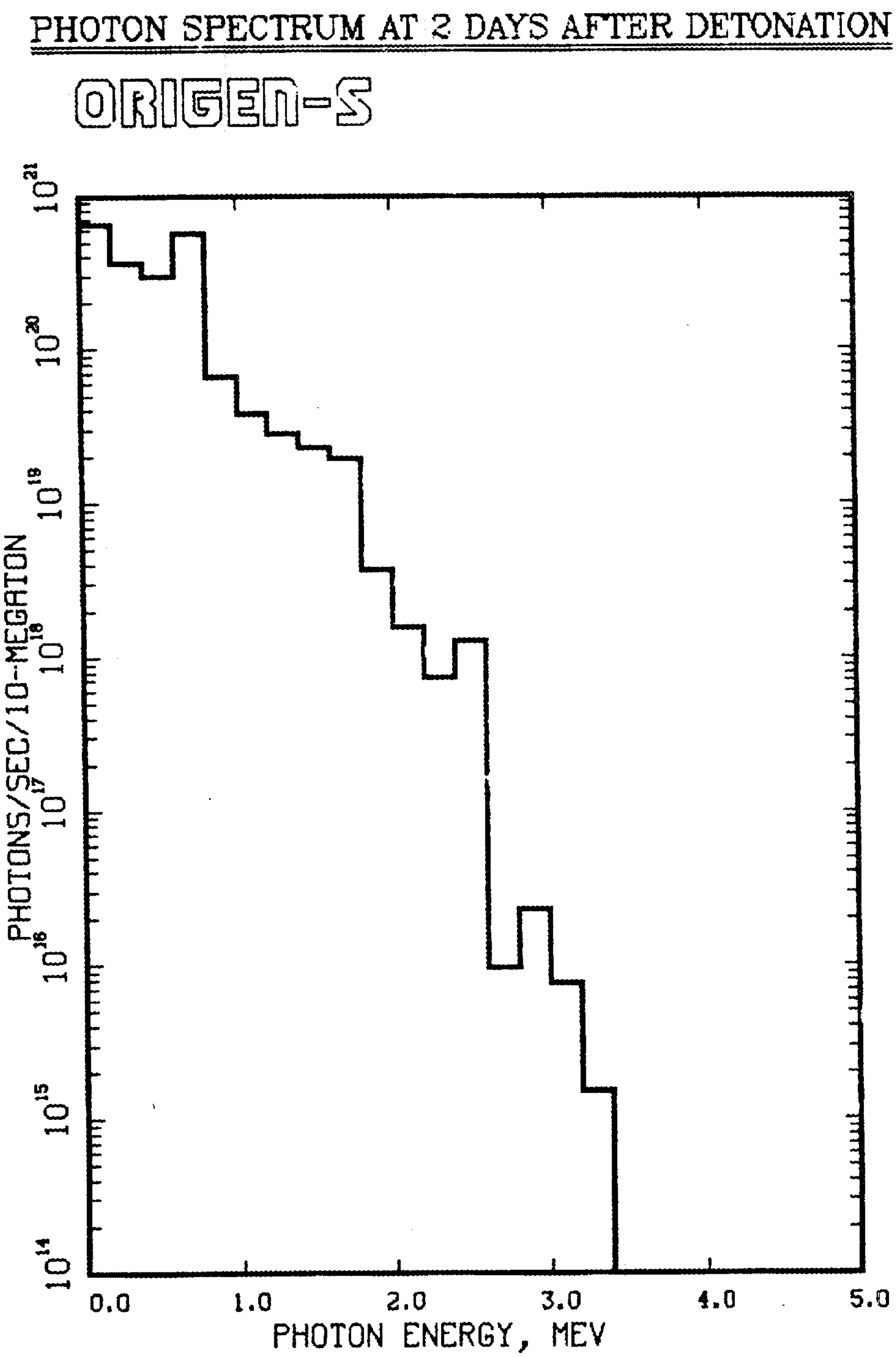

Figure 16. Theoretical evaluation of the gamma energy spectrum from fission products from a hypothetical 10 MT U^{235} warhead, at 2 d after detonation. From Hermann, 1988.

radioisotopes with greatly different half-lives can be more simply, though less accurately, represented by a power law decay.

The spectra shown in Figures 13 through 16 are THEORETICAL evaluations, and do not include fractionation or additional variations that may result during the physical process of fallout arriving on the ground, being blown by the wind or washed away by rain after deposition, becoming covered with snow, settling into soil or other materials, or being leached by rain or moisture in the soil. These latter processes are sometimes referred to as "weathering."

For operational purposes it would be useful to have a simple approximation that can be used with graphs or a pocket computer or calculator to estimate the average rate of decay for all contributions to the γ radiation from fallout. For many years it was assumed that the average rate of decay could be adequately represented by the simple formula given by equation (2), called the standard decay law. A widely accepted misinterpretation, discussed by Haaland (Ha87), of a basic theoretical paper by Way and Wigner (Wa48) compounded the use of this law. This simple decay function has been used to construct nomograms and graphs to calculate dose rates and exposures (ENW77, pp. 390–404, also many Civil Defense and military training manuals).

An examination of data shows that an approximation of the rate of decay of radiation from actual fallout on the ground from a single weapon during the first two days after detonation can vary between $t^{-1.1}$ and $t^{-2.4}$, without including the effects of wind or rain (Ha87). The causes of this variation can be attributed to fractionation, chemical composition of materials engulfed in the fireball, weapon materials, and neutron activation—all these factors contributing before fallout deposition. Additional factors, such as soil roughness, vegetation, terrain factors, instrument variations, and perhaps other factors as yet unknown, contribute to variation in measurement of radiation from the fallout after it is deposited. Variations in γ-decay approximations for the SHASTA test are illustrated in Figure 17. A summary of variations in measurements is given in Table 3.

These variations occur for simple fallout, resulting from one or more detonations all having the same time of detonation, so that all fallout has a common time of origin and the same age. When multiple detonations are involved, the fallout has different time origins, and therefore different ages, and the superimposed fallout has a slower resultant decay (Ha84).

One may conclude from these observations that attempts to estimate future radiation levels from fallout on the nuclear battlefield by using the simple $t^{-1.2}$ nomograms as presented in ENW77, p. 399, may produce misleading results. A new method is described in Chapter 11, which provides accurate results for a wide range of actual in-the-field decay rates by making use of actual radiation measurements taken at the locality.

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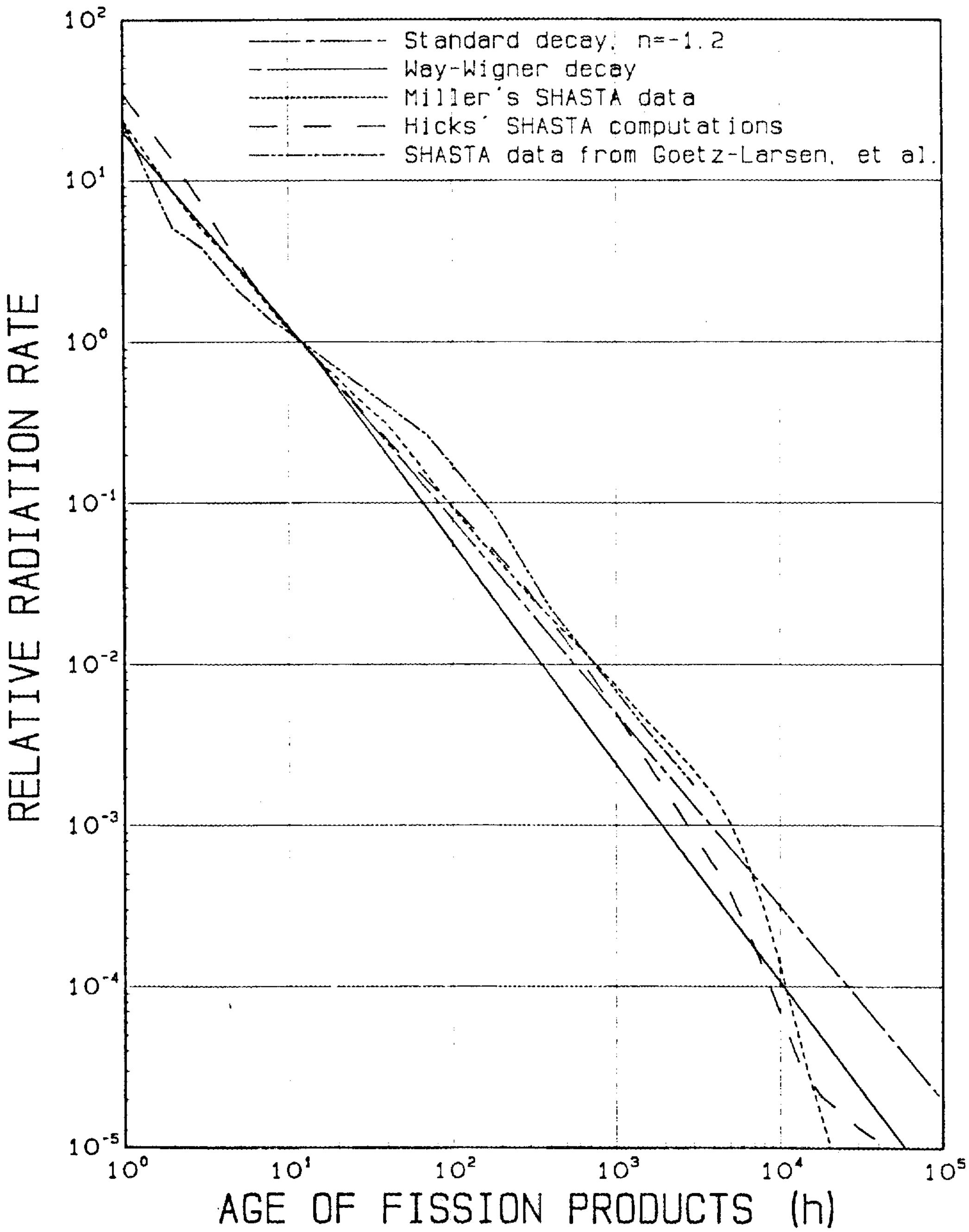

Figure 17. Comparison of gamma decay for fallout from the SHASTA test, using data sets by Miller and by Larsen and computations by Hicks. From Haaland, 1987.

TABLE 3

SUMMARY OF SELECTED GAMMA–DECAY BEHAVIOR

Data Source & Year	Type	Nuclear Source	Decay Approximation
Way-Wigner, 1948	Theory	100% fission	$t^{-1.2}$(15h); $t^{-1.4}$(- -).
BRAVO (1954) - Lesard (1985*)	Field	50/50 fission/ fusion	$t^{-1.5}$(7.2h); $t^{-1.3}$(53h); $t^{-1.4}$(24d).
UNION (1954) - Lesard (1985*)	Field	" " "	
BRAVO - Japanese analyses (1954-5) &Lesard (1985)	Field + theory	" " "	
BRAVO (1954) - Hicks (1984)	Theory	" " "	$t^{-1.5}$(9h); $t^{-1.1}$(12d)
PRISCILLA (1957) - Miller (1957)	Field & lab.	100% fission	$t^{-1.4}$(20h - 200d)
SHASTA (1957) - Larsen (1957)	Field	100% fission	$t^{-1.6}$(3h); $t^{-.9}$(3d)
SHASTA (1957) - Miller (1957-8)	Field & lab.	100% fission	$t^{-1.2}$(2h); $t^{-1.1}$(125d)
SHASTA (1957) - Hicks (1983)	Theory	100% fission	$t^{-1.5}$(12h); $t^{-1.1}$(25d)

*Field data from 1954 as extracted from a classified report & declassified by Lesard.

7. RADIATION DOSE FROM FALLOUT

7.1 INTRINSIC NATURAL SHIELDING AND THE GLASS–DISK REFERENCE CASE

Suppose that fallout is distributed uniformly on a hypothetical flat glass disk of one kilometer radius. A glass disk is specified here to emphasize that this case is a HYPOTHETICAL REFERENCE case, involving a very large smooth flat surface. Every small unit of area on the disk will contribute to the radiation received at a target point one meter above the center of the disk. Distance will reduce the radiation received at the target point because of two factors: 1) the solid angle from source point to target into which the radiation is emitted is reduced by greater distance (the inverse square law); and 2) γ rays are attenuated by absorption and scattering in air.

These two reduction factors constitute intrinsic natural shielding. They are called "intrinsic" because they result from natural, geometrical, and physical processes that are not obvious to everyone. Extrinsic natural shielding, such as terrain roughness and geophysical characteristics, will be discussed below. The terms "glass–disk" reference case and "intrinsic" and "extrinsic" natural shielding have not appeared previously in the literature to the author's knowledge, and are introduced here in an attempt for further clarification of a frequently misunderstood subject.

Straight–line radiation, or unscattered radiation, is reduced along its path in a medium by various interactions by a factor of $1/e$ (e=2.71828..., the base of natural logarithms) for each mean free path length. The mean free path of γ radiation in air at sea level ranges from 23 meters for 0.03 MeV photons to 228 meters for 3 MeV photons. A list of mean free paths for photons in air and other substances is given in Table 4, for photon energies from 0.1 to 5 MeV.

Some of the radiation that is emitted by the source in a direction AWAY from the target point may be scattered by collisions with air or ground molecules INTO the target direction. When a γ ray (photon) "bounces" off an air molecule, it is actually interacting with an electron associated with the molecule. The γ ray that results from this interaction will nearly always have a *lower* energy (never higher) and a different direction of travel than the initial γ ray. Because the scattered γ ray has lower energy as a result of the interaction, its mean free path in air will also be reduced. This contribution from scattered radiation, called buildup radiation, greatly complicates the calculation of the received radiation, and the situation is further complicated by the ground–air interface.

However, the two contributing reduction factors to intrinsic shielding predominate over the buildup due to scattering, and the radiation received at the target point (or detector) in this hypothetical case is almost entirely contributed from within a radius of 500 m on the glass disk, as illustrated in Figure 18. It may be seen from Figure 18 that 90% of the unscattered radiation arriving at the detector with a photon energy of 0.1 MeV is contributed from within a radius of 40 m on the disk, that of 1 MeV from within 80 m, and that of 5 MeV, within slightly less than 160 m.

TABLE 4

MEAN FREE PATHS OF PHOTONS IN VARIOUS MATERIALS FOR SELECTED ENERGIES

Photon Energy (MeV)	Mean free path (cm) in: Air	Flesh (or Water)	Sand	Bone	Concrete	Steel	Lead
0.1	5,300	6.1	4.0	3.0	2.1	0.4	0.02
0.3	7,630	8.5	6.0	4.7	3.2	1.2	0.2
0.5	9,370	10.4	7.5	5.8	4.0	1.5	0.6
0.6	10,100	11.2	8.1	6.3	4.3	1.7	0.8
0.8	11,500	12.7	9.2	7.2	4.9	1.9	1.0
1.0	12,800	14.1	10.2	8.0	5.4	2.1	1.3
1.5	15,800	17.4	12.6	9.8	6.7	2.6	1.7
2	18,300	20.3	14.5	11.4	7.7	3.0	2.0
3	22,800	25.3	17.9	14.1	9.5	3.5	2.1
4	26,500	29.3	20.3	16.3	10.8	3.8	2.1
5	29,700	33.0	22.5	18.2	11.9	4.0	2.1

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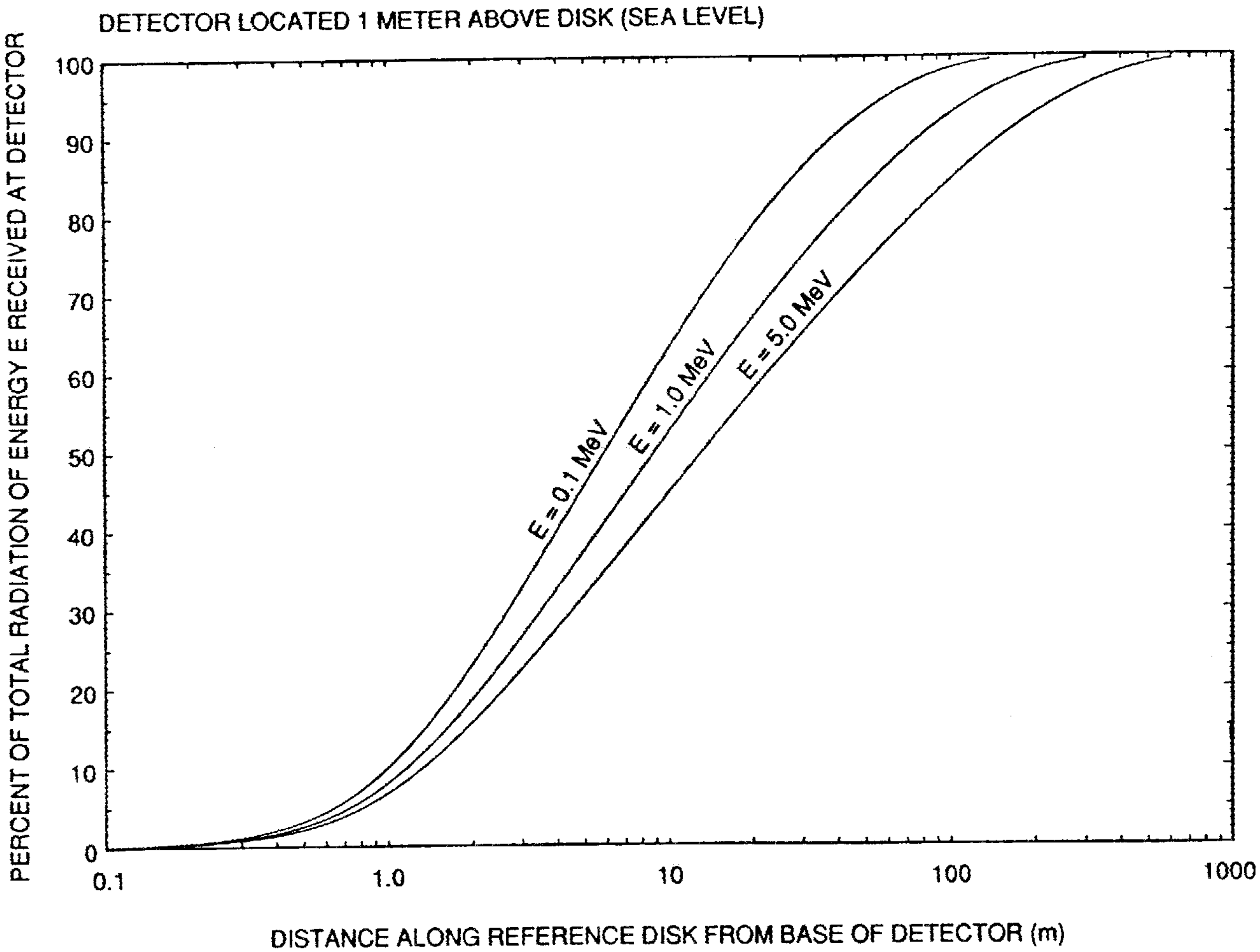

Figure 18. Contribution of *unscattered* radiation from uniformly distributed fallout on a hypothetical smooth, plane glass disk to the unscattered radiation received at a detector located 1 meter above the center of the disk, for three different photon energies, 0.1, 1.0, and 5.0 MeV.

7.2 SKYSHINE

In our hypothetical reference case of radiation deposition on a glass disk, all the radiation sources are BELOW the level of the target point that is located one meter above the center of the disk. If there were no scattering of radiation by the air, all the radiation received at the target point would be from below the edge of the disk. However, because of scattering, a fraction of the total radiation received will come from ABOVE the edge of the disk. This radiation is called skyshine. It is important to consider this component of radiation for troops in various posture on the battlefield, as, for example, in open foxholes.

Because of the scattering phenomenon for photons in air, a certain amount of radiation will be received from ALL directions. In Figure 19, results are shown for measurements of radiation in different directions from the vertical at a target point one meter above a flat surface uniformly contaminated with Cs^{137} (Cl60).[1] The detector has a resolution of 0.1 steradian, which means that it "sees" radiation coming in through a circle of about 36 cm diameter at a distance of one meter, corresponding to a half angle of about 20 degrees. A zero angle along the abscissa corresponds to the detector pointing straight up, indicating "skyshine." The solid line between angles of 100–180 degrees (the latter angle indicating that the detector is pointing straight down) was calculated for unscattered radiation because the detector at a height of one meter will see negligible amounts of scattered radiation arriving within these angular limits. These results indicate that 73% of the total dose is due to radiation received within 20 degrees above and below the horizon. This result is not expected to differ greatly when γ radiations other than those of Ba^{137} are included. Other related experiments and calculations are presented and discussed in considerable detail in Spencer et al., pp. 388-442 (Sp80).

As a rough rule for battlefield use, it may be assumed that the radiation level at a point at the center of a one–meter–diameter single–person foxhole one meter down from the surface will be about 15% of the radiation level at a point one meter above the surface. This radiation in the foxhole results from skyshine. At greater depths in the foxhole the radiation levels will decrease due to the smaller angle exposed to the sky.

7.3 EXTRINSIC NATURAL SHIELDING

The glass–disk reference case may be approximated in nature only on an ice–covered lake, with no snow present. In actuality, the deposition will probably be uneven due to local wind currents. Also, fallout will probably be deposited on a surface of greatly varying texture, such as a plowed field, a grassy area, crops, a forest, an urban area, or on a hilly or mountainous terrain. The γ radiation from the deposited fallout will be shielded by clods of dirts, stems or leaves of vegetation, by buildings, hills or mountains. This shielding may be called extrinsic natural shielding.

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[1] The radioisotope Cs^{137} is blamed for being a pernicious component of fallout, although it decays relatively harmlessly by low-energy β emission with a half-life of 30 years. The real villain is Ba^{137}, the principal daughter of Cs^{137}, which decays with a half-life of 2.6 minutes and emits a photon with 0.66 MeV energy.

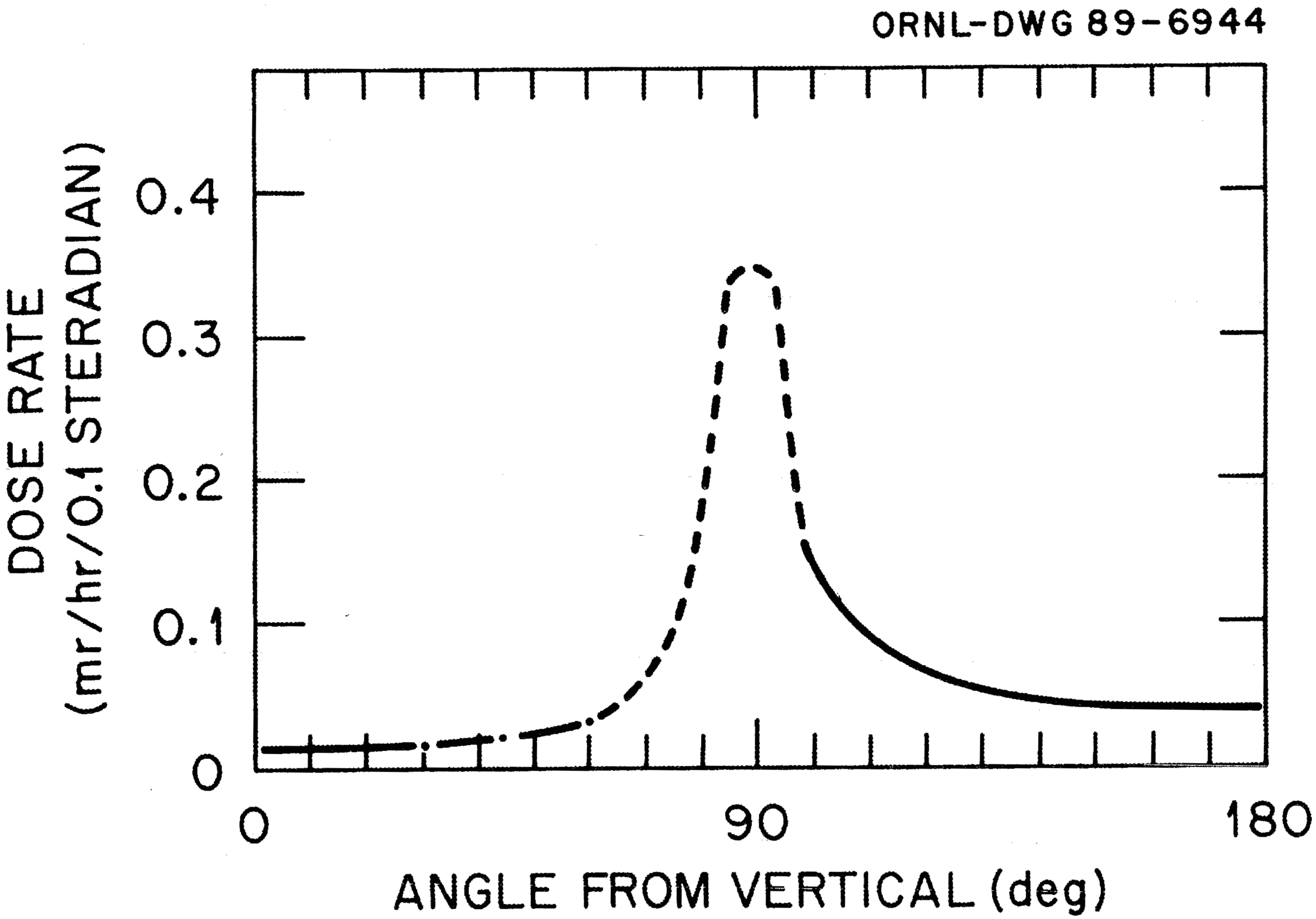

Figure 19. Variation of radiation intensity with angle measured from the vertical from Cs^{137} distributed uniformly on a smooth plane. From Clifford, 1960.

Ground roughness alone may reduce the radiation as estimated for the glass–disk reference case by factors of 2 or more (Cl64). Penetration of the fallout particles into the ground due to wind movement or leaching will increase the extrinsic natural shielding (Be68, Be80, Bu77, Fr68, Hu65). Analysis of radiation received from areas covered by vegetation is complicated by the possibility that the chemical composition of some kinds of fallout particles may cause the particles to stick to the leaves. For example, some of the fallout from BRAVO resembled quicklime (calcium oxide, a white caustic powder) in properties, and tended to adhere to surfaces. Fallout with similar properties may result when large quantities of concrete are vaporized by the fireball. For urban situations, structural perturbations may reduce dose rates by as much as 0.3 to 0.8, as compared with the glass–disk reference case (Co72).

7.4 STRUCTURAL SHIELDING—THE FALLOUT PROTECTION FACTOR

After fallout begins to arrive, there may be time for troops to find shelter in existing buildings, or for expedient shelters to be constructed, before a hazardous dose is accumulated. In most of the areas affected, the buildup of radiation to the maximum level will take at least a half hour, and possibly as long a several hours, depending on the yield of the detonation and the distance downwind (Mi69).

An indication of the protection given at a *specific location* in a structure against fallout radiation is given by the Fallout Protection Factor, or FPF. The FPF of a specific location is the ratio of the REFERENCE dose–rate at the target point of the glass–disk reference case, if located at ground level at the specific location, to the dose–rate measured at the specific location. Strong winds would blow some kinds of fallout off the glass disk, so there must be an assumption that the glass disk contains the same quantity of fallout as would fall on its area, and that the fallout is evenly distributed.

Typical FPFs are indicated in Figure 20 for various structures, for the specific location shown by the dot in the figure. Methods for estimating the FPFs of various structures, including foxholes and buried structures are given by Spencer, et al. (Sp80). Methods for finding the safest locations for radiation protection in a building in an actual fallout situation are described in *Radiation Safety in Shelters* (FEMA83).

We use the designation "FPF" rather than simply "PF" as used in older fallout literature, to distinguish from protection factors against initial nuclear radiation, which may be considerably different from the Fallout Protection Factor because of the difference in the type of radiation and energy spectrum. Using "FPF" rather than "PF" also prevents the natural misconception which may arise in nontechnical persons that a building rated with a high "Protection Factor" should provide protection against blast. This usage of "FPF" follows the recommendations given in *Radiation Safety in Shelters* (FEMA83).

The relative shielding effectiveness of various materials against the penetration of fallout γs is indicated in Table 4 for selected energies, in terms of the mean free paths of the γs within the materials. Mean free paths of air, flesh, and bone are included for comparison. A longer mean free path means that the material is more transparent to γ radiation.

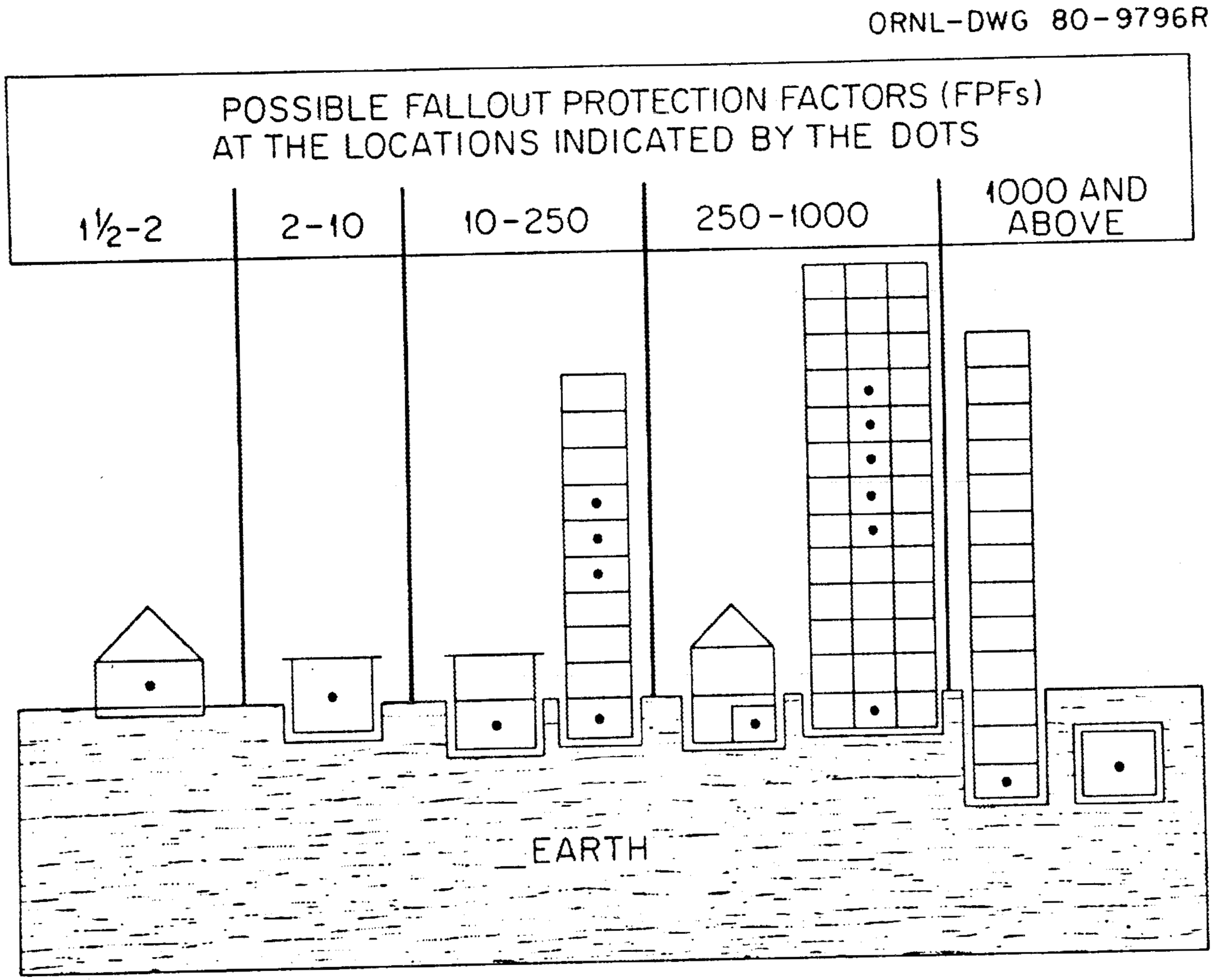

Figure 20. Fallout Protection Factors at specific locations (indicated by the dot) in various generic structures. From FEMA83.

For all the materials shown except lead, the length of the mean free paths vary from one material to another in a simple way that is roughly proportional to the inverse of the density. A simple principle for improving shielding is to increase the total mass, regardless of substance, between the source and the target.

For lead, the shielding capability against photons of less than about 0.6 MeV energy is much better than its greater density would indicate. The reason for this much increased shielding capability against the lower energy photons is that lead has a high Z number (Z=82), hence the photoelectric absorption component of its overall absorption coefficient remains strong for photons with energy up to about 0.6 MeV.

The design of various expedient shelters, the experience of building and living in them, and other expedient survival techniques, are described in *Nuclear War Survival Skills* (Ke87). A review of all types of shelters, including expedient shelter designs and tests conducted on them, is given by Chester and Zimmerman (Ch86).

7.5 FALLOUT GAMMA DOSE DISTRIBUTION IN HUMANS

An examination of a table of organ doses, as shown in Table 5, from radionuclides on a plane surface, moderately rough, shows, among other items, that, for a motionless person standing erect, the skeleton receives the largest dose for γ energies less than 0.5 MeV, and the skin and thyroid receive the largest doses for energies of 0.5 to 6 MeV (Ja88a and b). These calculated results may be compared with similar calculations for parallel beams of photons at various orientations (Jo73; Jo77), or for isotropic radiation (O'B76; Ko83), and with measurements using human-like phantoms, dosimeters and low-exposure-rate radiation sources (Be68). These numbers provide only a *relative* indication of organ doses when applied to an actual situation because of the motion and different postures of the subject, and variations in the field of radiation due to shielding, uneven fallout deposition, and weathering.

Organ dose-equivalents at a height of 1 m above-ground are relatively independent of source energy for all organs except the skeleton for photon energies from 0.1 to 10 MeV, and fall rapidly to zero for energies below 0.1 MeV. The skeleton, due to its high content of calcium, shows a peak in organ dose-eqivalent per kerma (kinetic energy of secondary radiation produced per unit mass) at 70 keV, as illustrated in Figure 21. It is because of this difference in photon absorption that medical x rays are able to "see" bones through flesh.

The data in Table 5 may be combined with the γ energy spectra shown in Figures 13 through 16 to get an idea of the relative contribution of various γ energies in a fission fragment source. In Table 5 the organ doses (pSv per photon m^{-2}) are the highest for 6 MeV photons, but, from the fission γ spectra, the numbers of photons at this energy range are negligible compared to those at lower energies. Photons of this energy are plentiful in INR (initial nuclear radiation), resulting from neutron capture in nitrogen of the air.

From the combination of dose and fission-γ spectral data, it appears that the photons in the energy range 0.2–1.2 MeV produce the largest equivalent dose, with a gentle peak in the vicinity of 0.7 MeV, the vicinity of the 0.66 MeV γ emitted by Ba^{137}, the daughter of Cs^{137}. This information is important for the design

TABLE 5

DOSE–FACTORS (pSv · m^2 per γ) FOR PHOTON EXPOSURE FROM PLANE SOURCES ON THE GROUND. EFFECTIVE DEPTH OF THE SOURCE IN THE SOIL IS 3 mm. H_E—ICRP IS THE EFFECTIVE DOSE EQUIVALENT (ICRP 1977, ICRP 1978). (From Jacob, et al, 1988)

Energy (MeV)	0.015	0.025	0.035	0.050	0.060	0.080
Female breast	$1.3\cdot10^{-7}$	$8.6\cdot10^{-6}$	$2.0\cdot10^{-5}$	$3.2\cdot10^{-5}$	$4.0\cdot10^{-5}$	$5.5\cdot10^{-5}$
Ovaries	$1.0\cdot10^{-8}$	$1.9\cdot10^{-7}$	$3.5\cdot10^{-6}$	$1.6\cdot10^{-5}$	$2.6\cdot10^{-5}$	$3.9\cdot10^{-5}$
Testes	$1.4\cdot10^{-7}$	$8.3\cdot10^{-6}$	$1.9\cdot10^{-5}$	$3.0\cdot10^{-5}$	$3.8\cdot10^{-5}$	$5.3\cdot10^{-5}$
Skeleton	$2.4\cdot10^{-8}$	$5.7\cdot10^{-6}$	$2.6\cdot10^{-5}$	$6.3\cdot10^{-5}$	$8.2\cdot10^{-5}$	$1.1\cdot10^{-4}$
Lungs	$1.0\cdot10^{-8}$	$1.4\cdot10^{-6}$	$9.5\cdot10^{-6}$	$2.5\cdot10^{-5}$	$3.4\cdot10^{-5}$	$5.1\cdot10^{-5}$
Red marrow	$1.0\cdot10^{-8}$	$9.1\cdot10^{-7}$	$5.0\cdot10^{-6}$	$1.6\cdot10^{-5}$	$2.4\cdot10^{-5}$	$4.1\cdot10^{-5}$
Thyroid	$1.6\cdot10^{-8}$	$2.8\cdot10^{-6}$	$1.2\cdot10^{-5}$	$2.6\cdot10^{-5}$	$3.6\cdot10^{-5}$	$5.5\cdot10^{-5}$
Total skin	$5.6\cdot10^{-7}$	$1.3\cdot10^{-5}$	$2.3\cdot10^{-5}$	$3.4\cdot10^{-5}$	$4.1\cdot10^{-5}$	$5.6\cdot10^{-5}$
Adrenals	$1.0\cdot10^{-8}$	$7.5\cdot10^{-7}$	$6.0\cdot10^{-6}$	$1.7\cdot10^{-5}$	$2.5\cdot10^{-5}$	$3.9\cdot10^{-5}$
Bladder	$1.0\cdot10^{-8}$	$1.5\cdot10^{-6}$	$7.6\cdot10^{-6}$	$2.1\cdot10^{-5}$	$3.0\cdot10^{-5}$	$4.6\cdot10^{-5}$
Brain	$1.0\cdot10^{-8}$	$5.5\cdot10^{-7}$	$6.2\cdot10^{-6}$	$2.0\cdot10^{-5}$	$2.9\cdot10^{-5}$	$4.5\cdot10^{-5}$
Stomach	$1.0\cdot10^{-8}$	$1.6\cdot10^{-6}$	$8.5\cdot10^{-6}$	$2.3\cdot10^{-5}$	$3.1\cdot10^{-5}$	$4.7\cdot10^{-5}$
Upper L.I.	$1.0\cdot10^{-8}$	$6.6\cdot10^{-7}$	$5.8\cdot10^{-6}$	$1.9\cdot10^{-5}$	$2.7\cdot10^{-5}$	$4.3\cdot10^{-5}$
Lower L.I.	$1.0\cdot10^{-8}$	$5.8\cdot10^{-7}$	$5.2\cdot10^{-6}$	$1.8\cdot10^{-5}$	$2.6\cdot10^{-5}$	$4.1\cdot10^{-5}$
Small I. +conts.	$1.0\cdot10^{-8}$	$4.4\cdot10^{-7}$	$4.9\cdot10^{-6}$	$1.7\cdot10^{-5}$	$2.6\cdot10^{-5}$	$4.1\cdot10^{-5}$
Kidneys	$1.0\cdot10^{-8}$	$2.3\cdot10^{-6}$	$1.0\cdot10^{-5}$	$2.3\cdot10^{-5}$	$3.1\cdot10^{-5}$	$4.6\cdot10^{-5}$
Liver	$1.0\cdot10^{-8}$	$1.2\cdot10^{-6}$	$7.8\cdot10^{-6}$	$2.2\cdot10^{-5}$	$3.1\cdot10^{-5}$	$4.6\cdot10^{-5}$
Pancreas	$1.0\cdot10^{-8}$	$3.1\cdot10^{-7}$	$3.8\cdot10^{-6}$	$1.6\cdot10^{-5}$	$2.5\cdot10^{-5}$	$4.1\cdot10^{-5}$
Spleen	$1.0\cdot10^{-8}$	$1.1\cdot10^{-6}$	$8.0\cdot10^{-6}$	$2.2\cdot10^{-5}$	$3.1\cdot10^{-5}$	$4.7\cdot10^{-5}$
Thymus	$1.0\cdot10^{-8}$	$2.3\cdot10^{-6}$	$9.6\cdot10^{-6}$	$2.4\cdot10^{-5}$	$3.2\cdot10^{-5}$	$5.0\cdot10^{-5}$
Uterus	$1.0\cdot10^{-8}$	$3.1\cdot10^{-7}$	$4.1\cdot10^{-6}$	$1.6\cdot10^{-5}$	$2.4\cdot10^{-5}$	$3.9\cdot10^{-5}$
H_E-ICRP	$6.1\cdot10^{-8}$	$4.6\cdot10^{-6}$	$1.3\cdot10^{-5}$	$2.7\cdot10^{-5}$	$3.6\cdot10^{-5}$	$5.2\cdot10^{-5}$

TABLE 5 (Continued)

Energy (MeV)	0.100	0.150	0.200	0.300	0.500	0.662
Female breast	$6.9\cdot10^{-5}$	$1.1\cdot10^{-4}$	$1.5\cdot10^{-4}$	$2.2\cdot10^{-4}$	$3.6\cdot10^{-4}$	$4.7\cdot10^{-4}$
Ovaries	$5.3\cdot10^{-5}$	$8.4\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$3.0\cdot10^{-4}$	$4.0\cdot10^{-4}$
Testes	$6.6\cdot10^{-5}$	$1.0\cdot10^{-4}$	$1.4\cdot10^{-4}$	$2.1\cdot10^{-4}$	$3.3\cdot10^{-4}$	$4.3\cdot10^{-4}$
Skeleton	$1.2\cdot10^{-4}$	$1.5\cdot10^{-4}$	$1.8\cdot10^{-4}$	$2.4\cdot10^{-4}$	$3.6\cdot10^{-4}$	$4.5\cdot10^{-4}$
Lungs	$6.5\cdot10^{-5}$	$1.0\cdot10^{-4}$	$1.4\cdot10^{-4}$	$2.1\cdot10^{-4}$	$3.4\cdot10^{-4}$	$4.5\cdot10^{-4}$
Red marrow	$5.6\cdot10^{-5}$	$9.1\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.1\cdot10^{-4}$	$4.1\cdot10^{-4}$
Thyroid	$7.1\cdot10^{-5}$	$1.1\cdot10^{-4}$	$1.5\cdot10^{-4}$	$2.3\cdot10^{-4}$	$3.6\cdot10^{-4}$	$4.8\cdot10^{-4}$
Total skin	$7.1\cdot10^{-5}$	$1.1\cdot10^{-4}$	$1.5\cdot10^{-4}$	$2.3\cdot10^{-4}$	$3.8\cdot10^{-4}$	$4.9\cdot10^{-4}$
Adrenals	$5.4\cdot10^{-5}$	$8.7\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$2.9\cdot10^{-4}$	$3.9\cdot10^{-4}$
Bladder	$5.9\cdot10^{-5}$	$9.2\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.2\cdot10^{-4}$	$4.2\cdot10^{-4}$
Brain	$6.0\cdot10^{-5}$	$9.6\cdot10^{-5}$	$1.3\cdot10^{-4}$	$2.0\cdot10^{-4}$	$3.4\cdot10^{-4}$	$4.4\cdot10^{-4}$
Stomach	$6.0\cdot10^{-5}$	$9.5\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.1\cdot10^{-4}$	$4.1\cdot10^{-4}$
Upper L.I.	$5.7\cdot10^{-5}$	$8.8\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$3.0\cdot10^{-4}$	$4.0\cdot10^{-4}$
Lower L.I.	$5.5\cdot10^{-5}$	$8.8\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$3.1\cdot10^{-4}$	$4.0\cdot10^{-4}$
Small I. +conts.	$5.5\cdot10^{-5}$	$8.7\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$3.0\cdot10^{-4}$	$4.0\cdot10^{-4}$
Kidneys	$6.0\cdot10^{-5}$	$9.3\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.1\cdot10^{-4}$	$4.2\cdot10^{-4}$
Liver	$6.1\cdot10^{-5}$	$9.5\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.2\cdot10^{-4}$	$4.2\cdot10^{-4}$
Pancreas	$5.5\cdot10^{-5}$	$8.7\cdot10^{-5}$	$1.1\cdot10^{-4}$	$1.7\cdot10^{-4}$	$2.9\cdot10^{-4}$	$3.8\cdot10^{-4}$
Spleen	$6.1\cdot10^{-5}$	$9.5\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.2\cdot10^{-4}$	$4.2\cdot10^{-4}$
Thymus	$6.2\cdot10^{-5}$	$9.8\cdot10^{-5}$	$1.3\cdot10^{-4}$	$2.0\cdot10^{-4}$	$3.3\cdot10^{-4}$	$4.3\cdot10^{-4}$
Uterus	$5.1\cdot10^{-5}$	$8.2\cdot10^{-5}$	$1.1\cdot10^{-4}$	$1.7\cdot10^{-4}$	$2.8\cdot10^{-4}$	$3.7\cdot10^{-4}$
H_E-ICRP	$6.6\cdot10^{-5}$	$1.0\cdot10^{-4}$	$1.4\cdot10^{-4}$	$2.1\cdot10^{-4}$	$3.4\cdot10^{-4}$	$4.4\cdot10^{-4}$

TABLE 5 (Continued)

Energy (MeV)	1.0	1.25	2.0	3.0	6.0
Female breast	$6.8 \cdot 10^{-4}$	$8.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
Ovaries	$6.1 \cdot 10^{-4}$	$7.4 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Testes	$6.2 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
Skeleton	$6.4 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Lungs	$6.6 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
Red marrow	$6.1 \cdot 10^{-4}$	$7.4 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Thyroid	$7.2 \cdot 10^{-4}$	$8.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$
Total skin	$7.2 \cdot 10^{-4}$	$8.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
Adrenals	$5.9 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
Bladder	$6.0 \cdot 10^{-4}$	$7.4 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Brain	$6.6 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
Stomach	$6.1 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Upper L.I.	$6.0 \cdot 10^{-4}$	$7.4 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Lower L.I.	$6.0 \cdot 10^{-4}$	$7.3 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Small I. +conts.	$5.9 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Kidneys	$6.2 \cdot 10^{-4}$	$7.6 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
Liver	$6.2 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Pancreas	$5.7 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Spleen	$6.3 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Thymus	$6.2 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$
Uterus	$5.6 \cdot 10^{-4}$	$6.9 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$
H_E-ICRP	$6.5 \cdot 10^{-4}$	$7.9 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$

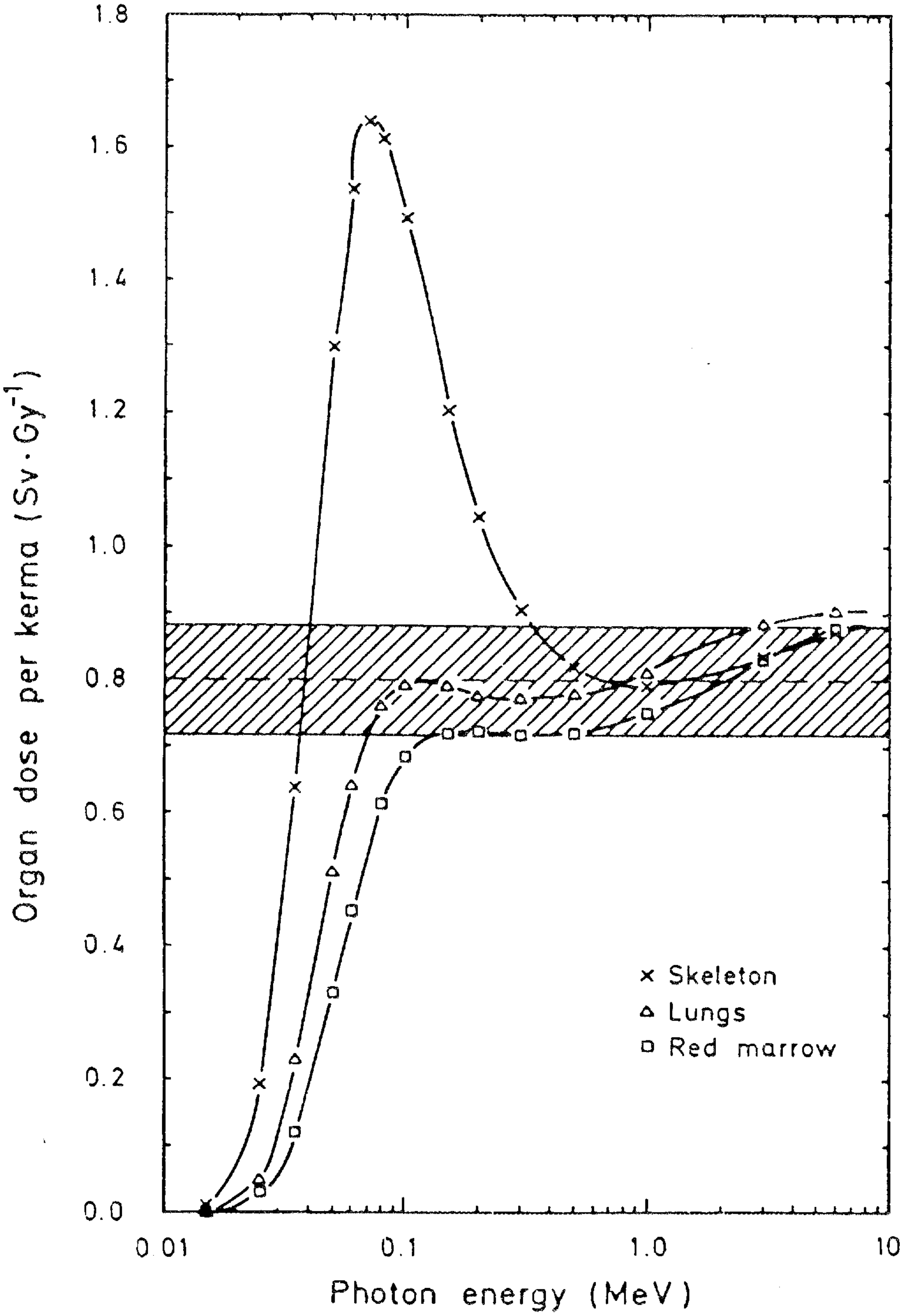

Figure 21. Dose equivalents for skeleton, lungs and red marrow per kerma free in air at a height of 1 m above-ground for an infinite plane source on a surface with roughness (effective source depth is 3 mm). From Jacob, et al., 1988.

of radiation protection instruments. A radiation detection device with a higher sensitivity to 6 MeV photons than to 0.7 MeV photons would give misleading results unless compensation were made for the sensitivity variation.

7.6 HUMAN EXPOSURE TO FALLOUT

The only nuclear detonation that produced fallout with observable harmful effects to humans was the BRAVO thermonuclear shot on Bikini atoll in the Pacific in 1954. This shot had a yield of about twice that expected, due to the unanticipated fission of U^{238} in the outer case of the weapon by high-energy neutrons from fusion processes. The fallout therefore went out further than expected, reaching the islands of Rongelap, Utirik, and Sifo, from which citizens had not been evacuated (Le85), and also falling on the Japanese fishing boat, the No. 5 Fukuryu Maru (Sh56). Because these people had no idea of the radioactivity in the fallout, no protective measures were taken. Rongelappians were evacuated by the US Navy on the 10th day after fallout arrived. It has been estimated that the maximum dose received by Rongelappians was about 175 rad (Le85). The primary early symptoms of fallout exposure among the Rongelappians were skin lesions due to β burns from fallout particles that adhered to the skin for a short period.

Contrary to widely held beliefs among the populace and press, there were no fallout injuries among the population of Hiroshima or Nagasaki from the atomic weapons exploded over them. Both detonations were airbursts in which the fireballs encountered no solid materials other than used in the bomb construction. These materials were completely vaporized and carried up into the atmosphere by buoyant forces.

However, a rain storm developed about a half hour after the detonation over each city (Co81; Ok87). This rain was black, presumably due to soot and dirt carried aloft by fires. Some radioactive materials were deposited by the rain, because low levels of radiation were detected in radiation measurements taken at downwind locations about 48 days after the detonation (Ok87). The estimated maximum unit-time reference dose rates are given as 0.5–14 R/h for the Nagasaki downwind area, and 0.1 to 1.8 R/h for Hiroshima. The low level of these estimated radiation rates indicate that only a small portion of the nuclear debris cloud was intercepted by the rain clouds in either case. Harmful effects of exposure by humans to this radiation would not be expected and was not reported. The cause of radiation illness in the Hiroshima population resulted from exposure to initial nuclear radiation from the detonation and residual radiation produced by neutron activation, not from fallout.

8. FALLOUT RADIATION HAZARD

8.1 BETA RADIATION

Beta burns will result if the skin is allowed to become dirty or grimy with fallout particles that are less than a few days old, and this dirt is not washed off for a period of several hours (Le85; Mi71). Early symptoms of such skin contamination include itching and burning sensations. Darkened or raised skin areas or sores may appear within one or two weeks. After two weeks or more, there may be a temporary loss of hair. The greater the exposure, the earlier the symptoms will appear. Beta burns will not be a problem if fallout particles are brushed or washed off promptly. Wearing clothing such as gloves, hats or helmets, scarves, face-masks, and long-sleeved garments will help to prevent fallout particles from collecting on the skin. Within a few days after fallout has arrived, its radioactivity will have decayed sufficiently that β radiation will not be a hazard under most circumstances. It may be a problem in the first few weeks if a person must lie or crawl on the ground, and the skin becomes covered with dust which is not removed for many hours, as may be necessary in some military operations.

8.2 GAMMA RADIATION

Because human exposure to γ radiation from fallout is usually accumulated over a period of hours to days, the movement of the body in the radiation field will usually result in exposure of the entire body to the radiation (Ad71; Be72; Cl70). According to NCRP Report No. 42 (NCRP74), a whole-body exposure of 50-200 R of γ radiation may result in radiation sickness. Because of the approximate numerical equivalence between R and cGy for γ skin dose (ICRU62), the levels for sickness reported in units of roentgens in NCRP 42 will be given here in units of cGy to conform with SI usage. According to NCRP 42, p. 37, the exposure units in roentgens can be converted approximately to absorbed dose units in rads at the midline of the body by multiplying the number of R units by 2/3. This conversion is substantiated by measurements by Beck, et al. (Be68). The same conversion factor applies for converting the exposed surface (area not shielded by arms or legs) tissue dose in cGys to midline dose in cGys.

Table 5 may be consulted to estimate dose to other organs. By using the exposure factors for the stomach and skeleton at a γ energy of 0.662 MeV, the comparable factor for bone marrow is 3/4; i.e., the exposure units in roentgens (or cGy to exposed surface tissue) can be converted approximately to absorbed dose units in rads (or cGys) in bone marrow by multiplying the number of R units (or exposed surface tissue cGy units) by 3/4.

Because of repair mechanisms within the body, a whole-body radiation dose of 600 cGy spread out uniformly over a period of 20 years would not cause any radiation sickness. But if this exposure were received over a brief period of a week or less, it would probably result in death, especially if clinical care were not available. It is evident that the *rate* of radiation exposure is very important in producing injury

that may result in death. Careful evaluation by Morris and Jones (Mo89) of all available data for radiation exposure to mammals has resulted in the data for man shown in Table 6. Exposure levels for LD_{05}, LD_{50}, and LD_{95} are shown for various exposure rates. LD_{50} is the whole-body radiation exposure level which would be lethal to 50% of a large number of normal males adults, in this case, without clinical support. The wide limits for 95% certainty in the data, as shown in Table 6, indicate the lack of data on this subject.

Some persons may become very sick within a few weeks after exposure for a week or less to a certain amount of γ radiation, but others may not feel any serious effects. If the dose is less than 50 cGy, the injury from radiation should not produce symptoms in anyone. Some persons irradiated in this dose range might experience loss of appetite and nausea, but this could also be the result of anxiety and fear.

The medical profession has distinguished five clinical levels of severity of acute radiation effects correlated with the amount of brief whole-body γ exposure (NCRP74). These levels are briefly described here and summarized in Table 7.

(1) **Level I, Whole-Body Gamma Dose Producing 50-200 cGy Exposed Surface Tissue Dose.** Less than half of the persons receiving this dose experience nausea and vomiting within 24 h. Afterwards, some may tire easily, but otherwise there are no further symptoms. Less than 5% need medical care. Any deaths that occur after this radiation dose are probably due to additional medical complications a person might have at the same time, such as infections and diseases, injuries from blast, or burns.

(2) **Level II, Whole-Body Gamma Dose Producing 200-450 cGy Exposed Surface Tissue Dose.** More than half of the persons receiving this dose experience nausea and vomiting and are ill for a few days. This illness is followed by a period of one to three weeks when there are few if any symptoms (latent period). At the end of the latent period more than half of those exposed experience loss of hair. Radiation damage to the blood-forming organs results in a loss of white blood cells, increasing the chance of illness from infections. Most persons in this category need medical care, but more than half will survive without treatment. The chances for living are better for those with smaller doses and those who get medical care. More than half are sick the first few days, but less than half die.

(3) **Level III, Whole-Body Gamma Dose Producing 450-600 cGy Exposed Surface Tissue Dose.** Most of the people receiving this dose experience severe nausea and vomiting, and are very ill for several days. The latent period is shortened to one or two weeks. The main episode of illness which follows is characterized by much bleeding from the mouth, throat, and skin, as well as loss of hair. Infections such as sore throat, pneumonia, and enteritis are common. People in this group need intensive medical care and hospitalization to survive. Fewer than half will survive in spite of the best care, the chance of survival being poorest for those who receive the largest exposures.

(4) **Level IV, Whole-Body Gamma Dose Producing 600 to over 10000 cGy Exposed Surface Tissue Dose.** This dose produces an accelerated

TABLE 6

PREDICTIONS OF LETHAL DOSES (cGy TO EXPOSED SURFACE SKIN) FOR 70 Kg MAN, ASSUMING NO CLINICAL SUPPORT.[a]

(Adapted from Table 3, Morris and Jones (Mo89))

Lethal dose	Limits for 95% certainty (percent)	Dose rate to exposed surface skin (cGy/hr) or exposure rate (R/hr)							
		3000	1200	600	300	120	60	10 (extrapolated)	2.68 (extrapolated)
LD_{05}	+114 −53	150	175	195	215	250	280	360	435
LD_{50}	+78 −44	245	275	300	325	365	400	480	545
LD_{95}	+87 −46	340	375	405	435	480	520	625	730

[a]Converted to cGy to exposed surface skin by multiplying data for cGy to marrow by 4/3, and rounding to nearest 5.

TABLE 7

LEVELS OF SICKNESS AND PROBABLE CONDITIONS OF MOST PEOPLE AFTER BRIEF WHOLE–BODY EXPOSURE TO GAMMA RADIATION AS INDICATED BY SURFACE TISSUE DOSE

Exposure Range Surface Tissue Dose (cGy)	Response	Probable condition of majority during engagement		Probable death rate during engagement	Comments
		Medical care required	Able to perform duties		
0-50	No symptoms	No	Yes	0	
50-200	Radiation sickness, Level I	No	Yes	Less than 5 percent	Deaths will occur in 60 or more days
200-450	Radiation sickness, Level II	Yes	No[a]	Less than 50 percent	Deaths will occur within 30-60 days
450-600	Radiation sickness, Level III	Yes	No[a]	More than 50 percent	Deaths will occur in about one month
More than 600	Radiation sickness, Levels IV & V	Yes	No	100 percent	Deaths will occur in two weeks or less

[a]Except during illness-free latent period.

version of the illness described for Level III. ALL persons exposed to this dose experience severe nausea and vomiting. Without medication, this condition can continue for several days or until death. Death can occur in less than two weeks. It is unlikely, even with extensive medical care, that many can survive.

(5) **Level V, Several Thousand cGy Whole-Body Gamma Dose.** Symptoms of rapidly progressing shock come on almost as soon as the dose has been received. Death occurs in a period of a few hours to a few days.

8.3 THE PENALTY TABLE

Table 8 shows a simplified system for managing radiation dose accumulation in fallout fields, based on experience based on clinical effects of exposure to radiation (NCRP74). Examples of the use of the "Penalty" table are given in Appendix II of NCRP Report No. 42., *Radiological Factors Affecting Decision-Making in a Nuclear Atack* (NCRP74).

Case C of the Penalty Table indicates that 50% may die if the accumulated radiation exposure in one week is 450 R (or, the exposed skin dose from the whole-body radiation is 450 cGy). If this dose were accumulated at a constant rate, the rate would be 2.68 cGy/hr, corresponding to the last column in Table 6, where the LD_{50} dose is shown to be 545 cGy. There is little discrepancy here, actually good agreement, considering the uncertainty of the data. Dose accumulation from fallout is VARIABLE, the highest rate of exposure occurring in the first few hours after fallout arrives. Over half of the 450 cGy exposure accumulated in a week will be received in the first day.

Consider a situation where fallout arrives at a location at H+4, fallout is completed at H+8, the decay rate is $t^{-1.4}$, and the exposure rate is such that the integrated exposed surface skin dose in one week is 450 cGy. At a time of H+8 the dose rate will be 28 cGy/hr, for which the LD_{50} is 430 cGy by extrapolation of data by Morris and Jones. From this example, it is evident that the Penalty Table provides a good guideline for control of radiation exposure from fallout, and it will be valid over a wide range of circumstances.

TABLE 8

THE PENALTY TABLE[a]

Medical care will be needed by—	Accumulated radiation exposure (R) in any period of a	b	c
	One week	One month	Four months
A NONE	150	200	300
B SOME (5 percent may die)	250	350	500
C MOST (50 percent may die)	450	600	—

[a]This table is taken from *Radiological Factors Affecting Decision-Making in a Nuclear Attack*, National Council on Radiation Protection and Measurements, Report No. 42.

9. COMPARISON BETWEEN PROMPT AND FALLOUT RADIATION EXPOSURE

9.1 SOURCE DIFFERENCES

Five categories of major differences between radiation from fallout and INR (initial nuclear radiation) consist of 1) time factors; 2) area covered; 3) direction of radiation; 4) type of radiation; and 5) spectrum. These categories are listed and briefly described in Table 9.

Time factors. Certain types of missiles, such as ICBMs and SLBMs, may provide a few seconds warning by leaving a visible trail in the atmosphere as they descend to their target. Taking quick cover in a foxhole, ditch, culvert, or a pool of water could provide life-saving shielding. Troops may have no warning from the INR from a nuclear cannon shell or a short range missile. In either case, the major pulse of INR will reach the troops within milliseconds after the detonation and will be mostly completed within a second. Troops who have not taken cover should attempt to do so even after exposure to the first pulse, because there will be continuing intense γ radiation for the following minute from fission fragments. After about one minute the rising fireball will carry the fission fragments to such a height that γ radiations reaching the ground will be negligible. The decrease in γ radiation reaching a person on the ground results from a combination of diminishing solid angle and increased air shielding due to increasing distance, and rapid decay of the radiation sources.

In contrast, fallout warning may be obtained minutes to hours in advance of arrival, from observation or a communication concerning an upwind ground detonation. Even if advance warning of its arrival is not received, there will be time for getting into shelters if warning is obtained directly from the observation of falling particles in conjunction with an increase in the readings of radiation ratemeters. Detection of the arrival of fallout is discussed in *Radiation Safety in Shelters* (FEMA83).

After fallout has arrived in an area, a lethal dose can be accumulated only by remaining in an unshielded area for many minutes to many days. Thus, another type of time factor difference between fallout and INR radiation is introduced: the rate of accumulation of radiation exposure. For INR, the dose rate of 3000 cGy/hr in Table 6 may be used to indicate lethality levels.* For fallout, the last two columns of extrapolated data are in the range that may be encountered.

It is important to recognize that the damaging effects of dose received from INR may be greatly exacerbated by subsequent dose received from fallout radiation. Evaluation of combat casualties from such combined dose will require a special methodology to assess equivalent doses from INR neutrons and γs, which must be modified by a time-dependent adjustment factor to include the effects of subsequent

* Private communication, T. D. Jones, Oak Ridge National Laboratory, 1989.

TABLE 9

COMPARISON OF INITIAL NUCLEAR RADIATION WITH FALLOUT RADIATION

	INITIAL NUCLEAR RADIATION	FALLOUT RADIATION
1. Time Factors		
Warning	Zero warning time to a few seconds	Many minutes to hours
Buildup time	Microseconds	Builds up over many minutes to hours
Duration	Less than a minute	Hazardous for days
2. Area Coverage		
	Less than a few square kilometers	Tens to hundreds of square kilometers
3. Direction		
	Strongly directional from detonation	Radiation from all directions, mostly horizontal
4. Type of Radiation		
Alpha	None	Some
Beta	None	Hazardous if in contact with skin for many minutes to hours
Gamma	Intense, high energy	Hazardous to unsheltered if exposed for minutes to hours
Neutrons	Intense, high penetrating	None
5. Spectrum		
Gamma	Early fission-fragment spectrum modified by air-capture γ spectrum	Fission spectrum only, varies with decay of component radioisotopes
Neutron	Broad neutron spectrum from zero up to 5-20 MeV depending on weapon	Essentially no neutrons

superposition of fallout γ dose. Additional research is required to develop such a methodology.

Area coverage. The range of lethal INR from nuclear detonations will range from around one kilometer from kiloton-yield warheads to not more than a few kilometers for multimegaton warheads. The area covered by lethal fallout can cover hundreds of square kilometers.

Direction. INR will be strongest from the direction of the detonation, however, there will be scattered radiation of lesser intensity from all other directions. A dosimeter on the shadow side of a person will read lower than one located on the side exposed directly to the detonation, due to body shielding. Because the INR pulse is of such short duration, body motions during the pulse will not significantly distribute the dose throughout the body. In contrast, fallout radiation will come from all the surfaces on which fallout has accumulated, and will continue for days. A dosimeter worn on one place on the body, such as the breastpocket, will give a fairly accurate indication of the wholebody dose due to the averaging effect of body motions during the long period of exposure (Ad71; Be73).

Type of radiation. INR contains a strong pulse of neutrons, with energies ranging from thermal up to several MeV, whereas fallout radiation has a negligible neutron component. Enhanced neutron weapons will produce up to 10-20 times higher neutron fluences than fission weapons, with energies up to 20 MeV. INR is composed of neutrons and γ radiation only. Fallout radiation has no neutron component, but is mainly γ radiation, with some hazard under certain circumstances from beta and alpha radiation.

Energy spectrum. Because there are negligible neutron radiations from fallout, only the γ spectra will be considered in comparing fallout with INR radiation. INR γs include energetic γs resulting from neutrons captured by air nuclei, which may comprise 40-60% of the total γs in INR. The fraction increases with range due to additional "conversion" of neutrons into γs by air-nuclei capture. This spectrum, which is almost flat (equal numbers of photons per unit energy width) from 1-6 MeV, strongly modifies the fission fragment spectrum during the first second after the detonation.

9.2 BIOLOGICAL DAMAGE

There is a basic difference in the way neutrons and γs interact with matter to produce the electrons, negative ions and free radicals that produce biological damage. Neutrons interact almost entirely with nuclei of atoms, whereas γs interact with the electrons. Neutrons in the INR spectrum usually scatter elastically upon collision with high-Z nuclei, without subsequent damage to surrounding matter. Biological damage results primarily from interaction of neutrons with hydrogen nuclei in water, causing ejection of a proton which produces many local ionizations, the number depending on the proton energy. Because of the high rate of local energy transfer in tissue or bone by energetic protons, the quality factor for biological damage by neutron radiation is greater than unity, and is dependent on the energy of the neutron.

Gammas in the low end of the fallout energy spectrum, below about 0.1 MeV, interact strongly with high–Z atoms through the photoelectric effect, interacting preferentially with those electrons having atomic binding energies near the photon energy. Gammas of higher energy interact with electrons primarily through direct collisions, called the Compton effect. γs with energy of 1.02 MeV or greater may also convert into a pair of electrons of opposite charge (positron and electron), a process called pair production. In all cases, free electrons are produced, which then produce ionization in the surrounding matter. The quality factor for biological damage by fallout γs is unity, except for those of energy less than 0.1 MeV that interact with bone. For the latter case, the quality factor is greater than one.

9.3 DOSIMETRY

Biological damage incurred by exposure to fallout γ radiation contributes (in a way that remains to be determined) to damage produced by exposure to INR. The dose received from neutrons in INR *must be properly converted* to equivalent dose before it may be added to the INR and fallout γ dose. The Penalty Table in Table 8 may then be used as a guide for decision–making. Fiber–electrosope dosimeters exist for γ dose measurement that are accurate, rugged, reliable, and inexpensive, but these instruments will provide a misleading reading if exposed to a combined pulse of γs and neutrons. Dosimetry for combined exposure to INR and subsequent fallout γs is an area that needs additional research and development.

10. FALLOUT RADIATION MEASUREMENT AND DOSE MONITORING

It should be evident from the above discussion that the geographical shape of the fallout radiation field is generally unpredictable, and the intensity of radiation may vary greatly from one location to another due to irregularities in deposition, weathering, and extrinsic shielding factors.

Because of the irregularities in radiation intensity, it is essential that every small group of persons moving together as a unit within a fallout radiation field should have amongst them at least one radiation rate meter. The rate meter will indicate whether the group is advancing into an area of increasing radiation intensity, thus permitting possible selection of a path of lesser radiation exposure, if consistent with the objectives of the group.

For the same reasons, it is essential that each person wear a dosimeter, and that a record is maintained of total exposure of each individual. The record should include the equivalent dose received from INR. If it is not possible to provide every person with a dosimeter, then group dosimetry should be practiced, whereby a dosimeter worn by one person is used to indicate dosage to each person in the group. Methods of group dosimetry and dosage recordkeeping for fallout radiation are described in *Radiation Safety in Shelters* (FEMA83).

11. FORECASTING RADIATION RATES AND EXPOSURE

In order to predict whether troops in a fallout situation may become subject to the "penalties" (e.g., 5% may die) specified by the Penalty Table, Table 8, it is necessary to have prediction schemes for radiation rates and exposures. Estimates of future radiation rates for regions in the immediate vicinity of the shelters will be needed for planning future missions into these regions. Future accumulated exposures of troops will be needed to determine who will be able to leave the shelter and for how long, without incurring additional radiation exposure penalty.

Methods for predicting radiation rates and exposure are described in ENW77, pp. 390–404. However, these methods require knowledge of the unit–time reference dose rate and assume that the radiation decays as $t^{-1.2}$. The unit–time reference dose rate cannot be measured, but it can be determined if the time of detonation is known and if the radiation decay rate is known (assumed to be $t^{-1.2}$ in ENW77). In a nuclear war, the detonation time of the explosion producing the fallout may not be known, and the decay rate of fallout radiation will probably not follow $t^{-1.2}$ for a number of reasons, as discussed above. Furthermore, the methods described in ENW77 do not apply if the radiation is emitted from fallout having two or more ages, resulting from ground bursts with two or more different times of detonation.

A method has been developed that circumvents these difficulties. This method will provide estimates of radiation exposure rates or cumulative exposures for intervals of a few days to a few weeks in the future to within +30% from actual measurements, provided there is no severe weathering. No assumptions are required as to time, yield, or location of bursts, the number of bursts, or on the rate of decay of radiation. The method is valid for a wide range of decay rates, for $n = 0.8$ to 1.6 in the simple decay formula t^{-n} (Ha87). The method requires a minimum of two radiation–rate measurements at the location, with the accuracy increasing with a greater number of measurements and a greater time between measurements. The improvement in accuracy with greater time between measurements may be assessed by consulting graphs in "Forecasting Radiation Rates and Exposure from Multi–Aged Fallout" (Ha87). If rain or heavy winds, sand, or snow modify the radiation field, then the series of measurements for predictions must resume after cessation of the perturbing weather phenomenon.

The nomogram in Figure 22 is intended to be self–explanatory. The nomogram may be used in different ways, as indicated by the examples printed on the chart. A potential user should work through these examples carefully.

Future accumulated exposures at a specific location resulting from fallout radiation at that location may be estimated by using the graph in Figure 23. The legend on the graph indicates how it is to be used in conjunction with the nomogram in Figure 22.

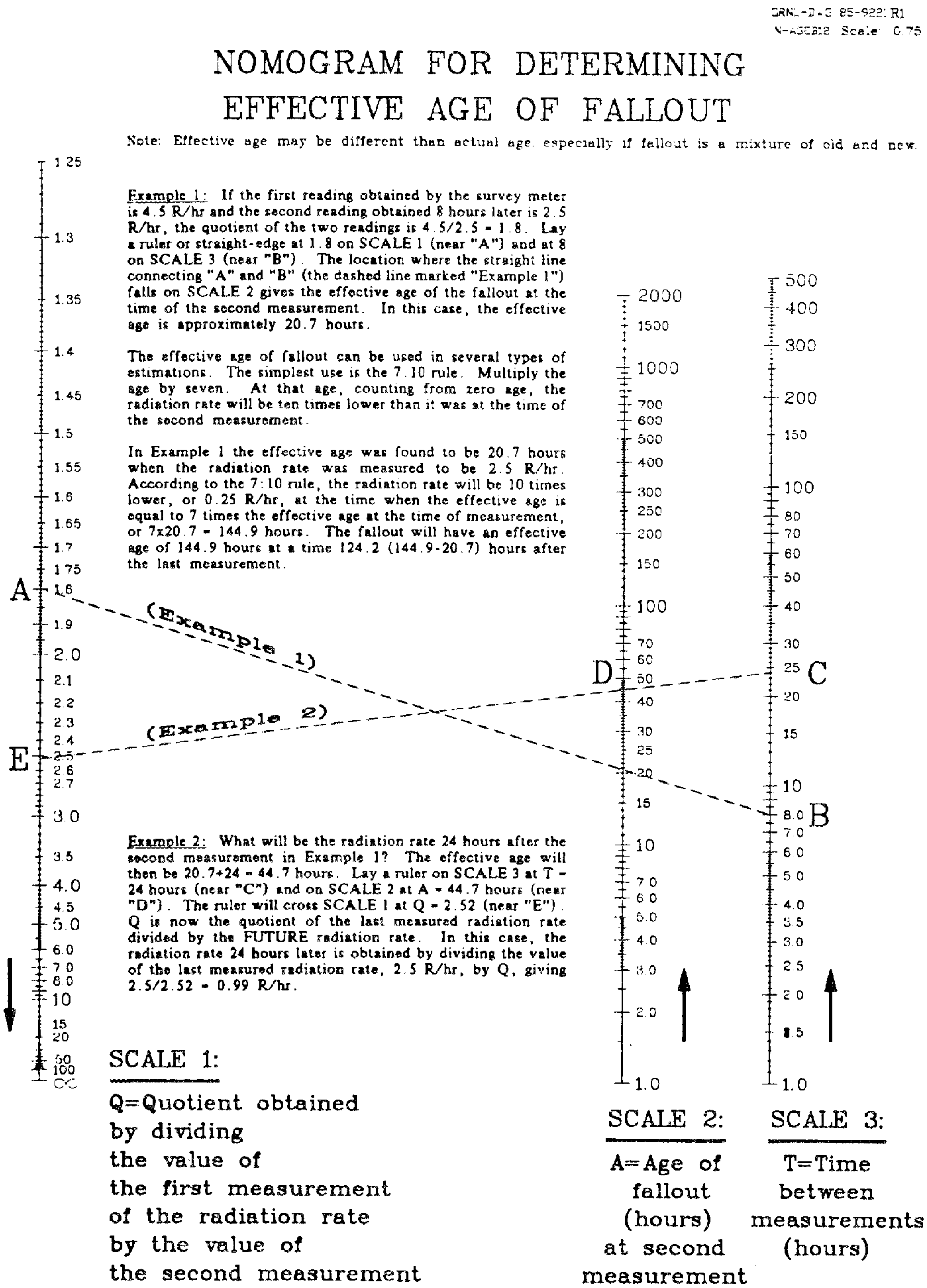

Figure 22. Nomogram for fallout radiation predictions. From Haaland, 1987.

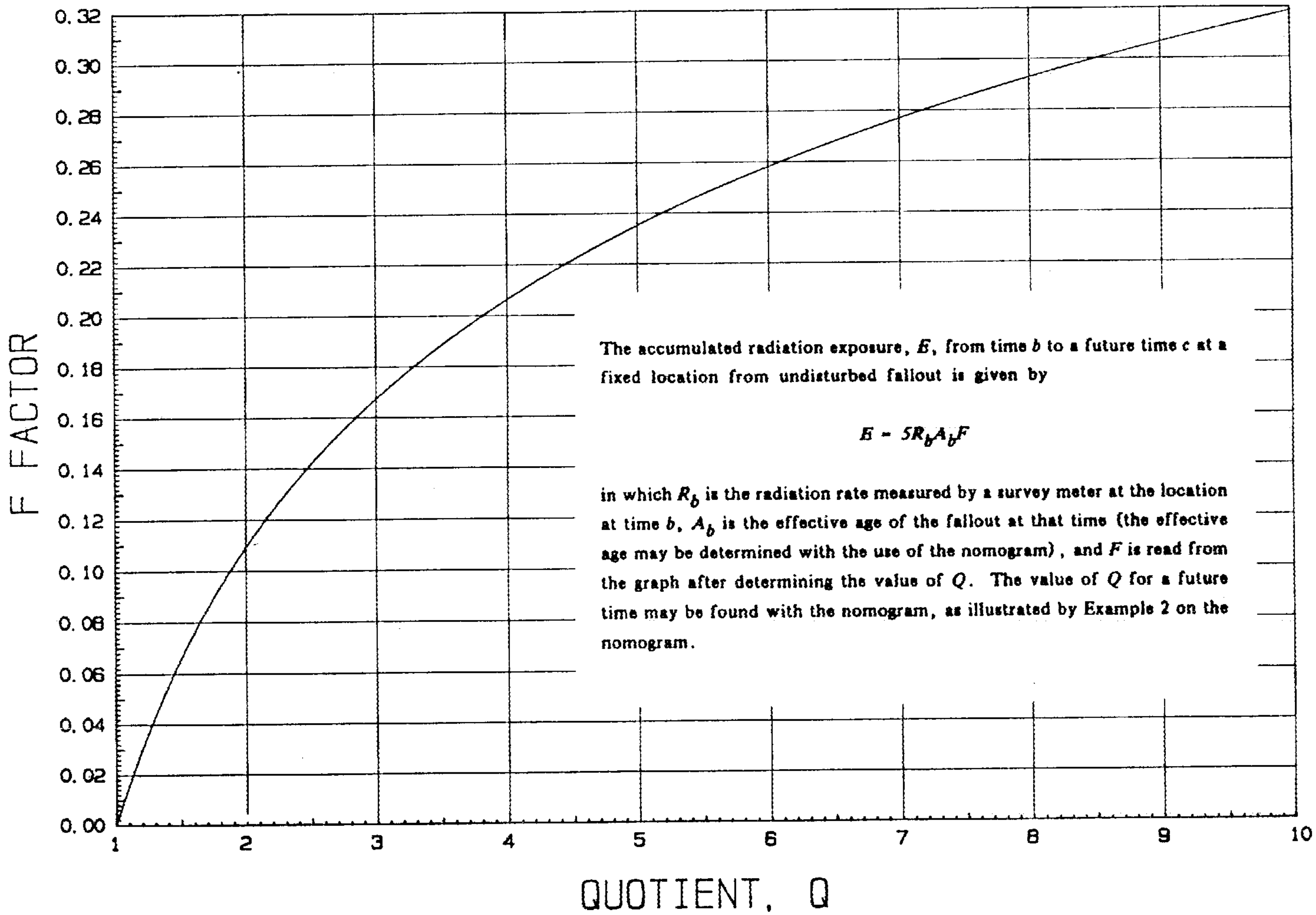

Figure 23. Graph for predicting accumulated radiation exposure. From Haaland, 1987.

12. DECONTAMINATION

The radiation exposure at a point in the open air is contributed by fallout on the ground and vegetation mainly from the region within a half kilometer of the point, as discussed previously. If the fallout can be washed or carried away, or covered with a shielding material, the radiation exposure at the point will be reduced. Washing the fallout away may be practical on ships, or on large paved sloping areas where there is an abundant water supply. Washing off the tops of high-rise buildings will reduce the radiation rate to occupants in upper stories. Carrying away the top layer of soil, or covering the ground with a layer of shielding material is expensive and time consuming, and may be entirely infeasible or impractical in a battlefield situation.

13. CONCLUSIONS

Fallout radiation is a potential hazard that must be considered for the nuclear battlefield. The magnitude of the area covered, the geographical shape, and the levels of radiation intensity cannot be precisely predicted. Protection by shelters is possible, and radiation dose management through the use of ratemeters and dosimeters will reduce the potential risk to troops.

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